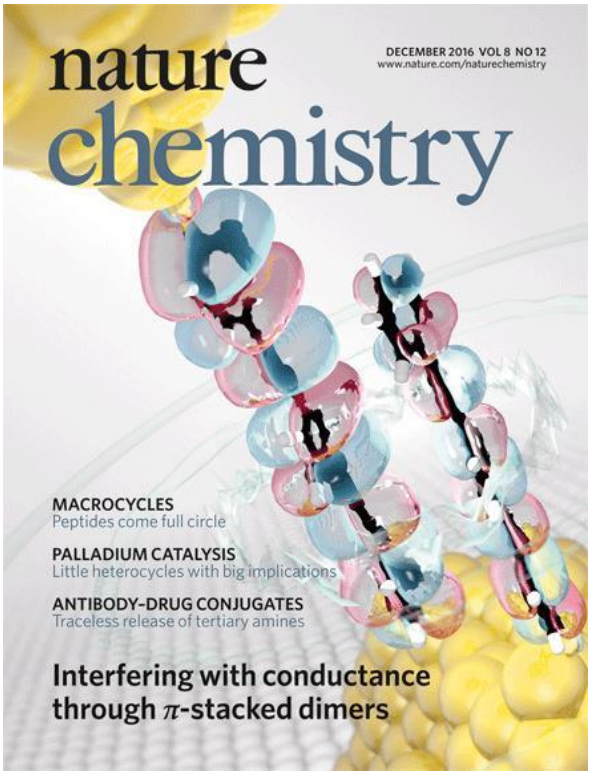
NWOI - 17.0100

Nederlandse Organisatie voor Wetenschappelijk Onderzoek

Annual report 2016

FOM programme nr. 141
'Quantum interference effects in single molecules'



Cover Nature Chemistry **8** (2016) p. 1099-1104: mechanical control over quantum interference in pi-stacked dimers of rod-like conjugated molecules (van der Zant/Grozema groups).

May 2017
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Content

1. Scientific results 2016

Based on the work in past years, the group of Grozema has focussed on theoretical design of donor-bridge acceptor systems that should exhibit quantum interference effects in a more convincing way. We have shown before that orbital symmetry arguments play an important role in this and new molecules have been proposed on basis of calculations (published, PCCP **18** (2016) 6773-6779). These molecules have now been synthesized and initial studies of the charge transfer properties have been performed. In these initial studies a clear difference between meta- and para-coupled benzene has been observed. This has previously not been possible since the interference effects were clouded by the orbital symmetry effects occurring in symmetric DBA systems. While quantum interference effect are mainly studied in single conjugated molecules, they have significant effects on the intermolecular charge transfer between molecules. This is related to the effect of orbital symmetry on the intermolecular electronic couplings. Experiments have been performed (van der Zant) on OPE3 molecules containing a single thiol anchoring group. The results yield very uncommon conductance traces where deep dips are observed in the conductance plateaus, in combination with plateaus that are much longer than can be expected for a single molecule. These conductance features are attributed to dimers of molecules between the electrodes. Theoretically (Grozema group), it was shown that deep dips in conductance traces can occur because of intermolecular quantum interference effects, depending on the mutual sign of the electronic coupling between the HOMO and LUMO orbitals of the two molecules. A detailed statistical analysis of the experimental conductance traces conforms that the theoretically predicted pattern indeed occurs. This shows that quantum interference effect can be manipulated mechanically by influencing the intermolecular conformation of two molecules. These results have been published in Nature Chemistry (Nature Chem., **8** (2016) 1099-1104).
In addition, based on previously published theoretical designs, the synthesis of a new single-molecule rectifier was completed and published (Org. Biomol. Chem., **14** (2016) 2439-2443). Single-molecule conductance studies in the group of van der Zant have shown that this rectifier exhibits an unprecedented rectification ratio of ~600 (Nanoscale, **8** (2016) 8919-8923). Furthermore, several molecular compounds have been screened in search for quantum interference effects; these studies include conductance measurements on thiophene curcuminoids (Chemistry – A European Journal, **22** (2016) 12808 – 12818), on molecules with a direct gold-carbon anchoring (Journal of the American Chemical Society, **138** (2016) 8465-8469) and indenofluorene-extended tetrathiafulvalenes for quantum interference in spin effects possibly resulting in Kondo blockade (J. Org. Chem., **81** (2016) 8406 – 8414).

The theory group in Delft focuses on two themes: (i) the alignment of the transport levels (mainly the frontier levels) to the chemical potentials of the metal leads in molecular junctions and (ii) the transport through molecular rectifiers, such as the ruthenium complexes studied in the Van der Molen group in Leiden. The research is carried out by the PhD student Jose Celis Gil and supervised by Jos Thijssen. The research on level alignment is progressing well. A second paper on this topic is ready for submission. In this paper, we demonstrate that for molecular junctions in the weak and strong coupling limit, a detailed analysis of the level alignment within DFT is possible without resorting to classical models for calculating the image charge effect. Furthermore, together with a master student, Jobbe van der Maessen, so-called hybrid DFT functionals, which give much better predictions for the molecular levels than the standard ones of DFT have been implemented and used in the quantum transport code that our group has implemented within the commercial BAND/ADF code. The results are promising and should soon lead to publication.
In another study, we have addressed the effect of water solvent on this alignment. This has been studied within different levels of sophistication for benzene di-amine-gold junctions as a reference. All our calculations which take into account the dielectric effect of the water predict an increase of the current as a result of adding water. Experiments in the Van der Zant group, however, show that water addition consistently leads to a reduction of the current. Extensive quantum chemical calculations focusing on the effect of water on the molecule-metal bond show that water drastically affects the bond between the amine and gold, leading to a lowering of the coupling between benzene and gold. In this study, several theoretical techniques have been combined which can in the future be used for different junctions. A paper is in preparation.
We have studied the ruthenium complexes that have been shown to lead to switchable rectifiers in the Van der Molen group. This work has had drawbacks due to a particularly tedious submission process (see the descrip-

tion by Van der Molen). Very elaborate calculations have very recently led to a picture which explains the experimental results. The explicit inclusion of water molecules was key to this work.

In the Van Ruitenbeek group (Leiden), PhD student Sasha Vrbica originally aimed at performing experiments in low-temperature UHV STM for the study of quantum interference in single molecules, under STM manipulation. The progress in this work was not satisfactory, largely because of recurring technical problems in the STM set up. In order to cope with this the project goals have been redefined, and several parallel projects have been started in order to mitigate risks.
Closest to the original programme is a project taken up in collaboration with the group of Jascha Repp at the University of Regensburg. The project involves an STM study of current-induced forces at the atomic level. Graphene nanoribbons are formed in-situ under UHV on a Au surface, followed by deposition of a small density of Co ad-atoms. Co atoms have a fair probability to be found on a nanoribbon, and by means of the STM tip current pulses are injected into the nanoribbons, at defined distances from an Co atom. Imaging the Co atom position after each pulse provides information on the current-induced displacement. We find two components in the motion of the atom: thermal diffusive motion, plus a directional component. Quantum interference has been predicted to give rise to a so-called Berry force, which we have not yet been able to single out. A first publication is in preparation, to be submitted in May 2017.
As a second project, in search for other suitable platforms that would give more precise control over molecular junction configurations we focused on graphene. From earlier work in the Van der Zant group we were aware of the advantages. In that work a junction was formed by controlled electroburning. While this demonstrates the potential the draw-back is that it does not allow testing many junctions within a reasonable time. In search for a solution we developed a technique by which the atomically thin edges of two graphene sheets, supported all the way to this edge, can be positioned at tunneling distance from each other. A manuscript has been written and will be submitted in April 2017. In this project we are collaborating with the group of Gregory Schneider, Chemistry Department in Leiden, and with Philips Research. In view of the potential of this technique as an alternative strategy for direct read-out of biopolymers we have submitted two patent applications.
Our interest in current-induced forces and graphene has attracted our attention to a publication (Yin et al., Nature Nanotechnology 9, 378, 2014) demonstrating the development of an electrical potential over a graphene sheet as a result of the motion of a water droplet over the surface. We have built a simple set up that reproduces and extends these results. The obvious question that we addressed is whether this effect can be inverted such as to move a droplet by size and direction of a current. The experiments suggest that this force is very small, and we are working on an interpretation. A publication is planned for July 2017.

In the Van der Molen group (Leiden), PhD student Huseyin Atesci focuses on quantum transport through and interference in Ru-complex molecules. For the interpretation of the results, there is continuous discussion with Jos Thijssen and his PhD student Jose Celis Gil (Delft) as well as with former Leiden postdoc, Bhadra Kaliginedi (now at EPFL, CH). Scientifically, 2016 has been very satisfying, with also a poster prize won at an international conference, but this has not translated yet to publications, as elaborated on below.
In this project, we investigate molecular monolayers self-assembled on top of an ITO substrate by conducting-probe (CP) AFM, at and above room temperature. In 2015, we had systematically studied a series of five different Ru-based molecules using Au and Pt tips. In one specific case, the so-called 2-Ru-N complex containing two Ru ions, a peculiar asymmetric behavior was found in current-voltage (IV)-curves. After further research, it turned out that the symmetry of the IV-curves is a strong function of the humidity of the environment. In dry N2, the IV's are near-perfectly anti-symmetric. In wet N2, however, the layers show strong rectification. In collaboration with Jos Thijssen's group, a joint manuscript was written and sent to Nature Nanotechnology in the summer of 2016. After a long struggle with referees (5 months) it was finally rejected, because the reviewers wanted more experimental evidence to support our model. We decided to set up an additional set of experiments. To distinguish chemical effects (Au-tip vs. ITO substrate) from geometrical effects (sharp tip vs. flat substrate), we decided to develop ITO-tips. This was a heavy time investment that finally paid off in winter 2016 (and 2017). We have now demonstrated that humidity-dependent rectification is geometry dependent, rather than a result of a chemical difference between tip and substrate. This has indeed helped us to update the details of our model. Note, however, that in its core the model remains the same: quantum overlap of two

near-degenerate HOMO orbitals leads to two localized molecular orbitals, one at each side of the molecule. Breaking the symmetry between those two LMO's leads to rectification behavior.
Thanks to the whole process, we now have a complete experimental data set in which both the tip geometry and chemistry is systematically varied. Scientifically, this has been very rewarding. Moreover, we now have enough data for three to four papers and a high-level dissertation for Huseyin Atesci. The backdrop has been, however, that these manuscripts are still to be submitted. It is planned to submit one paper in April 2017 and another two by June 2017.

2. Added value of the programme

- The collaboration between the groups of Grozema, Thijssen and Van der Zant has led to demonstration of a molecular rectifier; the whole sequence, including theoretical design, synthesis and conductance measurements is included, which would not have been possible for any of the individual groups. Intensive contact between the Van der Molen and Thijssen group has been very fruitful, leading to the demonstration and modelling of a humidity-dependent molecular rectifier with unprecedented rectification ratios ($\sim 10^4$) at high realitive humidities. The work in the Ruitenbeek group has profited from the exchange of knowledge concerning molecule deposition methods at Delft.
- The groups in the programme teach a joint lecture course which attracts very good students to our groups.
- Joint workshops and discussions are efficient and informative.
- A proposal is being drafted to organize an international workshop on quantum interference effects in charge transfer, in collaboration with the Lorentz center in Leiden.

3. Personnel

The contract of dr. Galan Garcia has ended and she has found a job in industry (Novaled, Dresden).

4. Publications

Text

12QIM01

a. Scientific (refereed) publications

- A gate-tunable single-molecule diode with high rectification ratios, Mickael L. Perrin, Elena Galan, Rienk Eelkema Joseph M. Thijssen, Ferdinand C. Grozema and Herre S.J. van der Zant, Nanoscale, 8 (2016) 8919-8923.
- Mechanically Controlled Quantum Interference in Individual π-stacked Dimers, R. Frisenda, V. Jansen, F.C. Grozema, H.S.J. van der Zant and N. Renaud, Nature Chem., 8 (2016) 1099-1104.
- C-Au covalently bonded molecular junctions using non-protected alkynyl anchoring groups, I.J. Olavarria-Contreras, M.L. Perrin, Z. Chen, S. Klyatskaya, M. Ruben and H.S.J. van der Zant, Journal of the American Chemical Society, 138 (2016) 8465-8469 (DOI: 10.1021/jacs.6b03383).
- Multiscale approach to the study of the electronic properties of two thiophene curcuminoid molecules, A. Etcheverry-Berríos, I. Olavarría, M.L. Perrin, R. Díaz-Torres, D. Jullian, I. Ponce, J.H. Zagal, J. Pavez, S.O. Vásquez, H.S.J. van der Zant, D. Dulić, N. Aliaga-Alcalde and M. Soler, Chemistry – A European Journal, 22 (2016) 12808 - 12818 (DOI: 10.1002/chem.201601187).
- Synthesis and Single-Molecule Conductances of Neutral and Cationic Indenofluorene-extended Tetrathiafulvalenes: Kondo Effect Molecules, M. Mansø, M. Koole, M. Mulder, I.J. Olavarria-Contreras, C. Lindholm Andersen, M. Jevric, S. Lindbæk Broman, A. Kadziola, O. Hammerich, H.S.J. van der Zant and M. Brøndsted Nielsen, J. Org. Chem. 81 (2016) 8406 - 8414 (DOI: 10.1021/acs.joc.6b01579).
- Insulator-protected mechanically controlled break junctions for measuring single-molecule conductance in aqueous environments, N. Muthusubramanian, E. Galan, C. Maity, R. Eelkema, F.C. Grozema, and H. S. J. van der Zant, Appl. Phys. Lett. 109 (2016) 013102-1-013102-4.
- Stretching-induced conductance increase in a spin-crossover molecule, R, Frisenda, G. H. Harzmann, J. A. Celis Gil, J. M. Thijssen, M. Mayor and H. S. J. Van der Zant, Nano lett., 16, 4733-4737, 2016.
- Image effects in transport at metal-molecule interfaces, C. J. O. Verzijl, J. A. Celis Gil, M. L. Perrin, D. Dulic, H. S. J. Van der Zant and J. M. Thijssen, The Journal of chemical physics, 143, 174106, 2015.

- Synthesis of unsymmetrically substituted 1,2-bis(4-bromophenyl)ethane wires: Key intermediates for single-molecule diodes, Elena Galan, Mickael L. Perrin, Ferdinand C. Grozema, Herre S.J. van der Zant and Rienk Eelkema, Org. Biomol. Chem., 14 (2016) 2439-2443.

b. Presentations at (inter)national scientific conferences
- H.S.J. van der Zant, Sending current through a single molecule, Invited talk, Minisymposium "Photochemistry", Delft (The Netherlands), May 2, 2016. 128.
- H.S.J. van der Zant, Single-molecule electronic components, keynote talk, ElecMol'16, 8th International Conference on Molecular Electronics, Paris (France), August 22-26, 2016.
- H.S.J. van der Zant, Transport characteristics of single all-organic radicals and spin-crossover molecules, Molecular Technology for the Design and the Control of Functionalities in Materials, invited talk, ICMM2016 satellite meeting, Tokyo (Japan), September 3, 2016.
- H.S.J. van der Zant, Spin spectroscopy of single molecules probed by an electric current, keynote talk, ICMM2016, Sendai (Japan), September 8, 2016. H.S.J. van der Zant, To what extent does confirmation bias play a role in single-molecule electronics?, invited talk, Quantum effects in Electronic Nanodevices (QUEEN) International Workshop, Oxford (UK), December 18, 2016.

12QIM02

a. Scientific (refereed) publications
- A gate-tunable single-molecule diode with high rectification ratios, Mickael L. Perrin, Elena Galan, Rienk Eelkema Joseph M. Thijssen, Ferdinand C. Grozema and Herre S.J. van der Zant, Nanoscale, 8 (2016) 8919-8923.
- Stretching-induced conductance increase in a spin-crossover molecule, R, Frisenda, G. H. Harzmann, J. A. Celis Gil, J. M. Thijssen, M. Mayor and H. S. J. Van der Zant, Nano lett., 16, 4733-4737, 2016.
- Image effects in transport at metal-molecule interfaces, C. J. O. Verzijl, J. A. Celis Gil, M. L. Perrin, D. Dulic, H. S. J. Van der Zant and J. M. Thijssen, The Journal of chemical physics, 143, 174106, 2015.

12QIM03

a. Scientific (refereed) publications
- A gate-tunable single-molecule diode with high rectification ratios, Mickael L. Perrin, Elena Galan, Rienk Eelkema Joseph M. Thijssen, Ferdinand C. Grozema and Herre S.J. van der Zant, Nanoscale, 8 (2016) 8919-8923.
- Mechanically Controlled Quantum Interference in Individual π-stacked Dimers, R. Frisenda, V. Jansen, F.C. Grozema, H.S.J. van der Zant and N. Renaud, Nature Chem., 8 (2016) 1099-1104.
- Tunable and Highly Efficient Light-Harvesting Antenna Systems Based on 1,7-Perylene-3,4,9,10-Tetracarboxylic Acid Derivatives, R. K. Dubey, D. Inan, S. Sengupta, E.J.R. Sudhölter, F.C. Grozema and W.F. Jager, Chem. Science, 7 (2016) 3517-3532.
- Synthesis of unsymmetrically substituted 1,2-bis(4-bromophenyl)ethane wires: Key intermediates for single-molecule diodes, Elena Galan, Mickael L. Perrin, Ferdinand C. Grozema, Herre S.J. van der Zant and Rienk Eelkema, Org. Biomol. Chem., 14 (2016) 2439-2443.
- Synthesis of unsymmetrically substituted 1,2-bis(4-bromophenyl)ethane wires: Key intermediates for single-molecule diodes, Elena Galan, Mickael L. Perrin, Ferdinand C. Grozema, Herre S.J. van der Zant and Rienk Eelkema, Org. Biomol. Chem., 14 (2016) 2439-2443.
- Computational design of donor-bridge-acceptor systems exhibiting pronounced quantum interference effects, Natalie Gorczak, Nicolas Renaud, Elena Galan, Rienk Eelkema, Laurens D. A. Siebbeles and Ferdinand C. Grozema, Phys. Chem. Chem. Phys., 18 (2016) 6773-6779.
- Insulator-protected mechanically controlled break junctions for measuring single-molecule conductance in aqueous environments, N. Muthusubramanian, E. Galan, C. Maity, R. Eelkema, F.C. Grozema, and H. S. J. van der Zant, Appl. Phys. Lett. 109 (2016) 013102-1-013102-4.

- Synthesis and Photophysical Properties of Conjugated and Non-Conjugated Phthalocyanine-Perylenediimide Systems, J. Follana-Berná, D. Inan, V.M. Blas-Ferrando, N. Gorczak, J. Ortiz, F. Manjón, F. Fernández-Lázaro, F.C. Grozema, and Á. Sastre-Santos, J. Phys. Chem. C, 120 (2016) 26508-26513.

b. Presentations at (inter)national scientific conferences
- F.C. Grozema, E. Galan, N. Gorczak, N. Renaud, H.S.J. van der Zant, R. Eelkema, Quantum interference effects in charge transfer and single molecule conductance, Invited lecture, Gordon conference on Electron donor-acceptor interactions, August 2016, Newport, RI, U.S.A.
- F.C. Grozema, Effect of molecular packing and structural dynamics on electronic properties of organic materials, Invited talk, Solvay Workshop "Charge, spin and heat transport in organic semiconductors", November 2016, Brussels, Belgium.

12QIM04

a. Scientific (refereed) publications
- Three publications in preparation: One publication on rectification due to orbital symmetry breaking in 2-Ru-N layers, measured with ITO tips, so that all effects are geometrical in nature. One that focuses on the 2-Ru-N system as a humidity sensor, with Au and Pt tips, discussing also the influence of chemical vs. geometrical asymmetry. And one that presents the much larger study of a series of five different Ru-based molecules.

b. Presentations at (inter)national scientific conferences:
- H. Atesci, V. Kaliginedi, S.J. van der Molen
  Switchable diode behaviour of Ru-complex self-assembled monolayers.
  Physica@FOM, Veldhoven, The Netherlands, January 19-20, 2016, Poster
- H. Atesci, Humidity-sensitive rectification in Ru-complex-based molecular junctions.
  CMD26 (European Physical Society), Groningen, The Netherlands, September 4-9, 2016, Presentation
- H. Atesci, V. Kaliginedi, J.A. Celil Gil, H. Ozawa, J.M. Thijssen, M. Haga, S.J. van der Molen
  Humidity-sensitive rectification in Ru-complex-based molecular junctions.
  8th International Conference on Molecular Electronics (Elecmol), Paris, France, August 22-26, 2016, poster.
- *Winner Poster Prize* at 8th International Conference on Molecular Electronics (Elecmol), Paris, France, 2016: H. Atesci, V. Kaliginedi, J.A. Celil Gil, H. Ozawa, J.M. Thijssen, M. Haga, S.J. van der Molen

12QIM05

a. Scientific (refereed) publications
- One publication is written and ready to be submitted; two are in preparation.

b. Presentations at (inter)national scientific conferences
- Sasha Vrbica, Tobias Preis, Nemanja Kocic, Jascha Repp, Jan van Ruitenbeek, "STM study of current induced forces in graphene nanoribbons on Au(111)" Dutch SPM Day 2016, 25 October, Nijmegen, the Netherlands.
- Jan van Ruitenbeek, "The ultimate limit of nanoscience: wiring single molecules", Distinguished Speaker of the Invited Evening Talk at the annual Nanotechnology Symposium in Bad Herrenalb, 6 October 2016.

5. PhD defences

None.

6. Valorisation, outreach and patents

The theoretical work is tied to the development of the transport module in the commercial ADF/BAND software, which is commercialized by Amsterdam-based company SCM (Software for Chemistry and Materials). Jose Celis Gil has written a manual which should make the module easily accessible to users of the software.

The work on graphene edge tunnel junctions has resulted in a collaboration with Philips Research, and with the group of Gregory Scheider (Leiden, LIC). A joint STW project application has been drafted, which will involve Philips Research, Leiden University Medical Center, and several small and medium size enterprises.

Patent applications: GB 1610183.4, STRUCTURE 10 june 2016. GB 1610187.5, METHOD 10 june 2016

Jan van Ruitenbeek was editor of a Thematic Series “Molecular Machines and Devices”, Beilstein J. Nanotechnology 7, 310-311 (2016).

Van der Molen has continued to be active in several physics outreach activities, e.g. via the 'wall formula' project, together with Ivo van Vulpen from NIKHEF. In 2016, both Snell's law and the Lorentz force formula appeared on Leiden walls. Furthermore, Van der Molen has been active in lecturing grade school kids (Junior Science Lab), high school children (Lapptop) and physics teachers (cursus kwantummechanica voor leraren).

The 2-Ru-N system (van der Molen group) forms a high-rectification device based on quantum transport at room temperature. It hence forms a very elegant example of how a molecular layer can become a functional device, measuring humidity in this case.

7. Vacancies

None.

FOM - 13.0224/4
datum: 01-01-2017

APPROVED FOM PROGRAMME

Number	141.
Title (code)	Quantum interference effects in single molecules (QIM)
Executive organisational unit	BUW
Programme management	Prof.dr.ir. H.S.J. van der Zant
Duration	2013 – 2018
Cost estimate	M€ 1.4

Concise programme description

a. Objectives

The main objective of this FOM programme is the investigation of quantum interference effects in molecular charge transport, thereby paving the way for new types of single molecule devices that exploit interference for novel functionality. The specific aims of this programme are:

1. To experimentally establish the fundamental nature and strength of quantum interference effects in single-molecule charge transport.
2. To investigate the sensitivity of interference to decoherence by electron-vibration interaction in these floppy systems.
3. To investigate the effects of quantum interference on physical properties of molecules.
4. To control these interferences either by chemical modifications to the molecule or by manipulating the interference effects in situ.

b. Background, relevance and implementation

Exploiting the rich design space of organic molecules for applications in future electronic devices is one of the main challenges in nanotechnology. During the last few years it has been demonstrated that it is possible to attach metallic contacts to individual organic molecules. This progress has triggered studies of transport through individual molecules, and from these measurements we now largely understand how vibrational modes, contact configurations, the length, and the conjugation of the molecule influence the molecule resistance. These properties, however, can to a large extent be explained by taking the molecule as a semiconducting building block; the specific functionality of a molecule is usually not taken advantage of. The next step and challenge in the field of molecular electronics is to exploit molecule-specific properties to obtain novel functionality. One feature of special interest is quantum interference that has very recently attracted a lot of theoretical attention and for which the first experimental studies now start to appear in the literature.
Researchers from Delft and Leiden form a team in which complementary expertise and experimental infrastructures are combined to achieve major steps forward in the understanding and control of quantum interference effects on the single-molecule level. Each member of the team has a strong track record, either in state-of-the-art molecular conductance measurements, time-resolved spectroscopic studies of charge transfer or non-equilibrium Green's function theory. Five PhD students (three in Delft and two in Leiden) and one postdoc (Delft) will be paid from the programme and work in close collaboration. By combining the variety of techniques available in the five groups, quantum interference effects in organic molecules will be studied in-depth, with independent data reproduction.

Funding

salarispeil cao per 01-01-2016

bedragen in k€	≤ 2016	2017	2018	2019	2020	≥ 2021	Totaal
FOM-basisexploitatie	841	280	280	-	-	-	1.401
FOM-basisinvesteringen	-	-	-	-	-	-	-
Doelsubsidies NWO	-	-	-	-	-	-	-
Doelsubsidies derden	-	-	-	-	-	-	-
Totaal	841	280	280	-	-	-	1.401

Source documents and progress control

a) Original programme proposal: FOM-12.1324
b) Ex ante evaluation: FOM-12.1474
c) Decision Executive Board: FOM-13.0219

Remarks

The final evaluation will be based on the self-evaluation report initiated by the programme leader and is foreseen for 2019.

HO par. HOZB

Subgebied: 100% NANO

Overview of projects and personnel

Workgroup FOM-D-44

Leader Prof.dr.ir. H.S.J. van der Zant

Organisation Delft University of Technology

Project (title + number) Three-terminal measurements of quantuminterference (12QIM01)

FOM employees on this project

Name	Position	Start date	End date
I.J. Olavarria Contreras	PhD	1 January 2014	31 December 2017

Leader Prof.dr.ir. H.S.J. van der Zant

Organisation Delft University of Technology

Project (title + number) Theoretical aspects of quantum interference 12QIM02

FOM employees on this project

Name	Position	Start date	End date
J.A. Celis Gil	PhD	15 June 2013	14 June 2017

Workgroup FOM-D-64

Leader Dr. F.C. Grozema

Organisation Delft University of Technology

Project (title + number) Charge transfer in quantum interference molecules 12QIM03

FOM employees on this project

Name	Position	Start date	End date
D. Inan	PhD	15 September 2014	14 September 2018

Workgroup FOM-L-22

Leader Prof.dr. J.M. van Ruitenbeek

Organisation Leiden University

Programme Quantum interference effects in single molecules

Project (title + number) Manipulation of single molecule quantuminterference 12QIM05

FOM employees on this project

Name	Position	Start date	End date
S. Vrbica	PhD	15 September 2013	14 September 2017

Workgroup FOM-L-39

Leader	Dr.ir. S.J. van der Molen
Organisation	Leiden University
Project (title + number)	Quantum interference in multi-molecular devices 12QIM04

FOM employees on this project

Name	**Position**	**Start date**	**End date**
H. Atesci	PhD	15 July 2013	14 July 2017