Programme title:

Quantum Geometry and Quantum Gravity

Acronym: QG

Principal Applicants:

Dr. John Barrett, University of Nottingham, Nottingham, UK **(contact person)**

Prof. Hermann Nicolai, Max-Planck-Institut für Gravitationsphysik, Golm/Potsdam.

Prof. Carlo Rovelli, Centre de Physique Theorique, Marseille.

Abstract: *(not more than half a page)*

The main objective of the programme is to stimulate the exchange of ideas between researchers pursuing different approaches to quantum geometry and apply the results to the study of quantum gravity.

The research programme will study several approaches to quantum gravity, namely loop quantum gravity, spin foam models, dynamical triangulations and matrix models. The common theme is the occurrence of quantum geometry in all these approaches. The research programme will study mathematical tools and techniques in non-commutative geometry and quantum groups and their applications to quantum gravity.

The planned activities are workshops and conferences, schools and programmes of research visits. These are designed to increase the level of interaction between existing research groups and to give a broad education in all the approaches to a new generation of young researchers.

Keywords: quantum geometry, non-perturbative quantum gravity, non-commutative geometry, spin foam models, matrix models.

Status of the relevant research, scientific context, objectives and envisaged achievements

Quantum Geometry arises when quantization techniques and principles are applied in a geometric context, such as group theory, gauge theories, particle physics and quantum gravity. The most physically profound of these applications is quantum gravity, the task of unifying Einstein's geometric conception of general relativity with quantum principles. The main focus of the network is understanding quantum geometry and using the results and techniques in the study of quantum gravity.

The recent history of quantum gravity is its development in two parallel paradigms, firstly as the quantization of general relativity, in which quantum geometry plays a central role, and secondly through the study of particle physics and strings, in which quantum geometry concepts are emergent. There is now some overlap in which the concepts fuse, such as the AdS/CFT correspondence in which quantum gravity in Anti-de Sitter space is related to Conformal Field Theory, or such as the non-commutative geometry that naturally appears as the geometry of open strings.

The quantization of general relativity is currently studied under two headings, loop quantum gravity, which emphasizes the role of space and the Hamiltonian formalism, and spin foam models, which emphasize the role of space-time and the path integral formalism. Although the conceptual frameworks differ, both approaches use the same mathematical techniques of spin networks and it is widely believed that these are complementary approaches to the same underlying theory.

<u>Loop quantum gravity</u> counts among its accomplishments the construction of a kinematical Hilbert space for quantum gravity on a spatial hypersurface of fixed time. Quantum states corresponding to black holes have been defined and there is a successful calculation of the black hole entropy. Operators measuring physical quantities such as area and volume have also been constructed and their spectra is known. The theory has some limited applications to scenarios where dynamics is required, such as quantum cosmology. It has also led to a valuable spin-off in classical relativity with the definition of an isolated horizon. A large limitation of the theory is that the dynamics is not known in the general case, and the related problem of constructing a semiclassical correspondence with general relativity is not solved, although there are encouraging partial results.

<u>Spin foam models</u> have their greatest success in 2+1 dimensional quantum gravity. Euclidean versions of this theory are well-defined and the focus of current research in this area is extracting the physics from the theory and comparing it to naïve expectations. The Lorentzian versions of the theory are incomplete and the centre of much current research activity, as the key questions in defining the theory relate to the representation theory of non-compact quantum groups. In 3+1 dimensions there are various spin foam models which have some features of quantum gravity. Their properties have been extensively investigated but at present it seems that all proposals have major issues unresolved. However the concept of spin foam model is very flexible and the exploration of all the possibilities is still at an early stage. There are closely related mathematical constructions in topology, homotopy theory, category theory and, again, quantum groups. These provide rich avenues for exploration. Of great importance for spin foam models are the techniques of what has became known as group field theory, which is a generalization of the matrix model approach to 2d gravity.

<u>Dynamical triangulations</u> can be considered as spin foam models of the most extreme simplicity; however the subject has hitherto been investigated as a separate subject. This approach to quantum gravity was studied in the 80's and 90's for Euclidean metrics in 2,3, and 4 dimensions. While the two-dimensional models gave encouraging results, the 3 and 4-dimensional models did not have phases which could be interpreted as 3 or 4-dimensional quantum geometries. This impasse was broken with

the recent proposal for Lorentzian dynamical triangulations. Numerical simulations indicate that these models do have a macroscopic geometry phase. In 2+1 dimensions the new Lorentzian dynamical triangulations have been shown to be described by exactly solvable matrix models.

Non-commutative geometry has been applied to deformations of classical geometries and groups, the study of gauge theories and the standard model of particle physics, and recently as the geometry of D-branes of open string theory in the background of B field. Non-commutative geometry has been proposed as an ultra-violet cut-off in quantum field theory. Field theoretical models on non-commutative manifolds such as the fuzzy sphere are examples of matrix models and are divergence-free. It was recently realized that some of them, like the Yang-Mills theory, are exactly solvable.

Quantum Groups are closely related to models of quantum gravity, particularly in 2+1 dimensions, where the deformation parameter is related to the cosmological constant. It is conjectured that 2+1 gravity with a negative cosmological constant is related to the representation theory of a certain non-compact form of sl2; a better understanding of this would open the door to exact calculations of the quantum properties of black holes in 2+1 dimensions. In 3+1 dimensions, quantum group deformations of the Poincare group are suggested to lead to modifications of the dispersion relations of special relativity which may have experimental signatures. Rapid development of these ideas would be possible with further progress in understanding the role of quantum geometry in quantum gravity.

Scientific Objectives and Envisaged Achievements

The main general objective is to stimulate exchange of ideas between researchers pursuing different approaches to quantum geometry. The main general envisaged achievements are (i) better understanding of quantum geometry through cross-fertilization of all the approaches listed above (ii) applications of quantum geometry to quantum gravity. More specifically, per subject or area of research:

Loop quantum gravity To understand the quantum group structure of the algebra of observables, to construct the correct dynamics, to study the emergence of macroscopic phenomena, and to understand the relationship with spin foam models.

Spin foam models To carry out computations of black hole and other physical properties in 2+1 quantum gravity. To determine and investigate proposals for spin foam models in 3+1 quantum gravity. To investigate the role of monoidal bicategories and braided monoidal bicategories in diffeomorphism invariant quantum field theories, and to construct non-trivial examples. To apply non-perturbative matrix model techniques, such as Borel summation, to group field theory.

Non-commutative geometry To explore applications of non-commutative geometry in quantum gravity, for example black hole entropy calculations. To explore the possibility of fusing the non-commutative standard model with spin foam models.

Quantum groups To apply the representation theory of deformations of the Lorentz, Poincare and de Sitter groups to quantum gravity in 2+1 and 3+1 dimensions. In 3+1, to determine experimental signatures of candidate theories of quantum gravity for which observational tests could be proposed.

Expected benefit from European collaboration in this area: There is a variety of European research groups pursuing different approaches to quantum geometry, with an extensive repertoire of expertise, comprising in total a large proportion of world research in the subject. However many of the strands are pursued in isolation and it is essential that the effort is combined and the level of interaction between the groups increases. It is also essential to educate a new generation of young researchers that are aware of all the approaches. Increased mobility is expected to lead to greatly enhanced academic career prospects for young researchers in countries other than their own. The proposed networking activity is designed to achieve these goals.

<u>European context:</u> There is a clear need for a European-wide network in this subject as there is currently no European programme which covers this key subject area. Some Marie Curie RTN programmes and ESF programmes have covered small parts of the proposed subject area (e.g. on non-commutative geometry and on discrete random structures), but these are now completed.

Proposed activities:

1. **Workshop** on "Quantum Geometry and Quantum Gravity", 3 for the period of the duration of the program.
2. **Conference** on "Quantum Geometry and Quantum Gravity", 4 for the period of the duration of the program.
3. **School** on "Quantum Geometry and Quantum Gravity", 2 for the period of the duration of the program.
4. **Short visits.** 20 visits per year each lasting 10 days.
5. **Long visit.** 2 visits per year each lasting 6 month.

Duration: 5 years

Budget estimate:

1. **Workshop:** 20 people meeting for 4 days.

Activity	Per day per person	Total per person	Total
meals	20 Euro	80 Euro	
accommodation	80 Euro	320 Euro	
travel		300 Euro	
all		700 Euro	14,000 Euro

Local administrative costs: 1,400 Euro.

2. **Conference:** 100 people meeting for 4 days. 20 invited speakers + 23 participants equals 43 participants receiving full support.

Activity	Per day per person	Total per person	Total
meals	20 Euro	80 Euro	
accommodation	80 Euro	320 Euro	
travel		300 Euro	

all		700 Euro	30,100 Euro

Local administrative costs: 3,010 Euro.

3. **School:** 30 students each staying for 10 days, together with 7 lecturers each staying 7 days.

Activity	Per day per student	Total per student	Per day per lecturer	Total per lecturer	Total
meals	20 Euro	200 Euro	20 Euro	140 Euro	
accommodation	40 Euro	400 Euro	80 Euro	560 Euro	
travel		300 Euro		300 Euro	
all		900 Euro		1000 Euro	34,000 Euro

Local administrative costs: 3,400 Euro.

4. **Short Visits:** 17 visits per year, each lasting 10 days.

Activity	Per day per visitor	Total per visitor	Total
meals	20 Euro	200 Euro	
accommodation	65 Euro	650 Euro	
travel		500 Euro	
all		1350 Euro	22,950 Euro

5. **Long visits:** 2 visits per year, each lasting 6 month. 1600 Euro per month + 500 Euro to each visitor in travel expences = 20,200 Euro per year.

6. **Programme Coordinator:** Appointment will be made at the post-doctoral level for a half-time post which would be expected to be held jointly with a half-time research post funded from other sources. The only cost under this heading is a half salary calculated for a postdoctoral researcher at age 30 at the University of Nottingham.
   At current exchange rates and allowing for 3% inflation this is 25,000 Euro per year.

Job description: The programme coordinator will work with the chair, steering committee, event convenors and ESF to

- administer the programme and produce required documentation
- organise the scientific activities
- edit the initial brochure and ongoing newletters
- develop and maintain the programme website
- liase with programme participants

7. **Publicity, Website and Publications:** The budget for publicity is the cost of producing the brochure and newsletters, calculated at 500 Euro per year. There are no additional costs for the website, as the salary cost is covered by the programme coordinator. There is no budget for publications as it is expected that research results and school notes will be published either on the web or by publishers at no cost.

8. **Steering Committee meetings**: There will be an initial meeting in Strasbourg, followed by annual meetings at the conference, to save on costs. The initial meeting will nominate an executive group which may meet by email conference. There is also a small budget for travel by the chair which is necessary to coordinate the programme. The cost of the initial meeting is 15 people with average travel and accomodation costs of 500 Euro; 15 x 500 = 7,500 Euro. This cost is averaged per year at 1,500 Euro per year. Subsequent meetings at the annual conference: it is anticipated that 5 members of the committee may not have travel supported by the conference. This gives a cost of 5 x 500 = 2,500 Euro per year. Finally the budget for necessary travel by the chair is 1,000 Euro per year. Total 1,500+2,500+1,000=5,000 Euro per year.

9. **External administrative costs:** Secretarial support is required for the chair and the programme coordinator. The budget is calculated at 10% the salary cost of a secretary at the University of Nottingham with 3% inflation allowance: 2,100 Euro per year, plus 850 Euro per year contribution to the office costs. Total: 2,950 Euro per year.

Total budget

Planned are 2 schools and 3 workshops; the total amount needed for these two activities in 5 years is 37,400 x 2 + 15,400 x 3 = 121,000 Euro. This is divided into 5 years, which gives the budget of 24,200 Euro per year for these two activities. The total for four conferences 4 x 33,110 is also divided by 5 to give 26,488 Euro per year.

Activity	Total **per year**
School and Workshop	24,200 Euro
Conference	26,488 Euro
Short Visits	22,950 Euro
Long Visits	20,200 Euro
Programme Coordinator	25,000 Euro
Publicity	500 Euro
Steering Committee	5,000 Euro

External Administrative Costs	2,950 Euro
All	127,288 Euro

To this amount the ESF 7.5 % administration fee of 9,547 Euro must be added.

PROPOSAL TOTAL: 136,835 PER YEAR

Annex 1-1

Curriculum Vitae: John Barrett

Address: School of Mathematical Sciences, University Park, Nottingham NG7 2RD, UK. Phone: +44 115 951 4956 Fax: +44 115 951 4951 email: john.barrett@nottingham.ac.uk

Present position: Reader in Applied Mathematics, University of Nottingham

Education:
1982-1985 Imperial College, London: PhD in Theoretical Physics
1979-1982 University of Cambridge: BA in Physics and Theoretical Physics (1st class)

Previous Positions:
1992-1998 Lecturer in Applied Mathematics, University of Nottingham
1989-1994 SERC Advanced Fellow.
1989-1992 Fellow, Girton College Cambridge.
1987-1989 Fellow of the University of Newcastle
1985-1987 Royal Society European Science Exchange and Tomalla Foundation Fellow, University of Zurich

Awards and honours:
Member of EPSRC college (2004-present)
Member of the London Mathematical Society

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Curriculum Vitae: Hermann Nicolai

Address: Max-Planck-Institut für Gravitationsphysik, Albert-Einstein-Institut, Am Mühlenberg 1, 14476 Golm, Germany. Phone: +49 (331) 567-7216 Fax +49 (331) 567-7297 email:Hermann.Nicolai@aei.mpg.de

Current position: Director and Scientific Member, Max-Planck-Institut für Gravitationsphysik, Potsdam-Golm

Education:
1975-1978 PhD in Physics, University of Karlsruhe
1971-1975 Diploma in Physics, University of Karlsruhe

Previous Positions:
1988-1997 Professor(C4) of Theoretical Physics, University of Hamburg
1986-1988 Professor(C3) of Theoretical Physics, University of Karlsruhe
1979-1986 Fellow and Staff member, CERN Theory Division
1978-1979 Assistant(Theoretical Physics) University of Heidelberg

Awards and honours:
Otto Klung Prize for Physics (1991)
Member of the Scientific Council, DESY (1993-1995)
Member of the Deutsche Physikalische Gesellschaft
Editor-in-Chief of Classical and Quantum Gravity (1998-2003)

Annex 1-3

Curriculum Vitae: Carlo Rovelli

Address: Centre de Physique Theorique, Campus de Luminy, Case 907, 13288 Marseille cedex 9, France. Phone +33 (0) 4 91 26 96 44 Fax +33 (0) 4 91 26 95 53
e-mail: rovelli@cpt.univ-mrs.fr

Current positions:
Professeur (1ere classe), Universite de la Mediterranee et
Centre de Physique Theorique de Luminy, CNRS, Marseille, France.
Member of the ``Institute Universitaire de France''.
Affiliated professor of History and Philosophy of Science, University of Pittsburgh, Pittsburgh PA, USA.

Education:
1983-1986 Universita di Padova Dottorato di Ricerca (Ph.D.) in Physics
1975-1981 Universita di Bologna Laurea in Fisica (with honors)

Previous Positions:
2000-pres Universitee de la Mediterranee Professuer (1ere classe)
1999-2000 Pittsburgh University Full Professor
1998-1999 CPT Luminy Directeur de Recherche
1994-1999 Pittsburgh University Associate Professor
1990-1994 Pittsburgh University Assistant Professor
1988-1989 Universita dell'Aquila Professore a contratto
1989 Sissa, Trieste Post-Doctoral position
1989 Syracuse University Visiting Fellow
1987 Yale University Post-doctoral Fellowship
1987-1988 Universita di Roma INFN Post-doctoral position
1987 Syracuse University Visiting position
1986 Imperial College London Visiting position

Awards and honours:
-- 1995 Xanthopoulos Award, Triennial International Prize in Relativity awarded to the best relativist under 40 years old.
-- Gravity Research Foundation, 1996 Second Award.
-- Chancellor Distinguished Research Award, University of Pittsburgh 1993
-- ``Idoneo'' al concorso Professore Universitario di Prima Fascia, Universita di Lecce, Maggio 2000.
-- Chiamata ``per chiara fama'' (Honor nomination) votata dal Consiglio di Dipartimento dell'Universita di Roma La Sapienza, Aprile 2002.

Annex 2

List of the 5 most relevant publications of the applicants during the last 5 years:

John Barrett:

John W Barrett, Christopher M. Steele. Asymptotics of relativistic spin networks. Class.Quant.Grav.20:1341-1362,2003

John W Barrett. Geometrical measurements in three-dimensional quantum gravity. Int.J.Mod.Phys.A18S2:97-113,2003

John C. Baez, John W. Barrett. Integrability for Relativistic Spin Networks. Class.Quant.Grav. 18 (2001) 4683-4700

John W. Barrett, Louis Crane. A Lorentzian Signature Model for Quantum General Relativity. Class.Quant.Grav. 17 (2000) 3101-3118

John C. Baez, John W. Barrett. The Quantum Tetrahedron in 3 and 4 Dimensions. Adv.Theor.Math.Phys. 3 (1999) 815-850

Hermann Nicolai:

Thibault Damour, Marc Henneaux, Bernard Julia, Hermann Nicolai. Hyperbolic Kac-Moody Algebra and Chaos in Kaluza-Klein Models. Phys.Lett. B509:323-330,2001

Arundhati Dasgupta, Hermann Nicolai, Jan Plefka. An introduction to the quantum supermembrane. Grav.Cosmol.8:1,2002, Rev.Mex.Fis.49S1:1-10,2003

T. Damour, M. Henneaux, H. Nicolai. E(10) and a small tension expansion of M theory. Phys.Rev.Lett.89:221601,2002

T. Damour, M. Henneaux, H. Nicolai. Cosmological Billiards. Class.Quant.Grav.20:R145-R200,2003

Alex J. Feingold, Hermann Nicolai. Subalgebras of hyperbolic Kac-Moody algebras. Kac-Moody Lie algebras and related topics, 97--114, Contemp. Math., 343, Amer. Math. Soc., Providence, RI, 2004

Carlo Rovelli:

Roberto De Pietri, Laurent Freidel, Kirill Krasnov, Carlo Rovelli, Barrett-Crane Model from a Boulatov-Ooguri Field Theory over a homogeneous space. Nucl.Phys. B574:785-806,2000.

Donald Marolf, Carlo Rovelli, relativistic Quantum Measurement. Phys.Rev. D66:023510,2002.

Carlo Rovelli, Simone Speziale, Reconcile Planck scale discreteness and the Lorentz-Fitzgerald contraction. Phys.Rev.D67:064019,2003.

Winston Fairbairn, Carlo Rovelli, Separable Hilbert space in loop quantum gravity. J.Math.Phys. 45:2802-2814,2004.

Florian Conrady, Luisa Doplicher, Robert Oeckl, Carlo Rovelli, Massimo Testa. Minkowski vacuum in background independent quantum gravity. Phys.Rev. D69:064019,2004.

Annex 3

Names and affiliations of the envisaged Steering committee:

1. Austria: *Prof. Harald Grosse*, Institute for Theoretical Physics, University of Vienna, Vienna.
2. Belgium: *Prof. Marc Henneaux*, Universite Libre de Bruxelles, Bruxelles.

3. Denmark: *Prof. Jan Ambjorn*, Niels Bohr Institute, Copenhagen.
4. France: *Prof. Carlo Rovelli*, Centre de Physique Theorique, Marseille.
5. Germany: *Prof. Hermann Nicolai*, Max-Planck-Institut für Gravitationsphysik, Golm.
6. Greece: *Prof Theodosios Christodoulakis*, Department of Physics, University of Athens.
7. Italy: *Prof. Mauro Carfora*, Dipartimento di Fisica Nucleare e Teorica, Pavia.
8. Netherlands: *Prof. Gerard 't Hooft*, Institute for Theoretical Physics, Utrecht.
9. Poland: *Prof. Jerzy Lewandowsk*i, Uniwersytet Warszawski, Warsaw.
10. Portugal: *Prof. Roger Picken*, Instituto Superior Técnico, Lisbon.
11. Spain: *Prof. Victor Aldaya*, Instituto Carlos I de Física Teórica y Computacional, Universidad de Granada, Granada.
12. Switzerland: *Prof. Jürg Fröhlich*, Institute for Theoretical Physics, ETH, Zürich.
13. Sweden: *Prof Ingemar Bengtsson*, Department of Physics, Stockholm University
14. United Kingdom: *Dr. John Barrett*, School of Mathematical Sciences, University of Nottingham, Nottingham.

Annex 4

Names and affiliations of researchers/research groups that want to participate in the Programme's activities:

Note: in addition to those listed, research groups contain numerous postdocs and research students.

1. Austria: Harald Grosse, Harold Steinacker, Institute for Theoretical Physics, University of Vienna, Vienna.

2. Belgium: Marc Henneaux, Faculte des Sciences, Physique, Universite Libre de Bruxelles, Bruxelles.

3. Denmark: Jan Ambjorn, Niels Bohr Institute, Copenhagen.

4. France: (a) A. Perez, C. Rovelli, Centre de Physique Theorique, Marseille. (b) L. Freidel, Laboratoire de Physique, Ecole Normale Superiore de Lyon. (c) P. Roche, E. Buffenoir, K. Noui, Laboratoire de Physique Mathematique et Theorique, Universite de Montpellier.

5. Germany: (a) Hermann Nicolai, Martin Bojowald, Thomas Thiemann, Max-Planck-Institut für Gravitationsphysik, Golm. (b) Martin Reuter, Institute of Physics, University of Mainz. (c) Claus Kiefer, Institute for Theoretical Physics, University of Cologne.

6. Greece: (a) T. Christodoulakis, Department of Physics, University of Athens. (b) A. Dimakis, Department of Financial and Management Engineering, University of the Aegean. (c) I. Raptis, Department of Mathematics, University of Athens.

7. Italy: (a) R. De Pietri, Dipartimento di Fisica, Universita degli studi di Parma, Parma. (b) M. Carfora and A. Marzuoli, Department of Nuclear and Theoretical Physics, University of Pavia. (c) J. Nelson, Department of Theoretical Physics, University of Turin. (d) G. Amelino-Camelia, Dipartimento di Fisica, Università Roma 'La Sapienza'

8. Netherlands: G. 't Hooft, R. Loll, Institute for Theoretical Physics, University of Utrecht.

9. Poland: (a) J. Lewandowski, J. Pawelczyk, Institute of Theoretical Physics, Uniwersytet Warszawski, Warsaw. (b) J. Kowalski-Glikman, Institute for Theoretical Physics, University of Wroclaw. (c) J. Jurkiewicz, Institute of Physics, Jagellonian University

10. Portugal: (a) J. Mourão, R. Picken, Department of Mathematics, Instituto Superior Técnico, Lisbon. (b) M. Mackaay, Department of Mathematics, University of the Algarve. (c) A. Mikovic, Department of Mathematics and Computational Sciences, Universidade Lusofona, Lisbon. (d) P. Moniz, J. Velhinho, Department of Physics, Universidade da Beira Interior, Covilhã.

11. Spain: (a) F. Barbero, G. Mena Marugan, Inst. Matematicas Fisica Fundamental, Madrid. (b) V. Aldaya, Instituto Carlos I de Física Teórica y Computacional, Universidad de Granada.

12. Sweden: (a) I. Bengtsson, Department of Physics, University of Stockholm. (b) J. Mickelsson, Department of Physics, Royal Institute of Technology, Stockholm.

13. Switzerland: (a) J. Fröhlich, Theoretical Physics, ETH Zurich (b) G. Felder, D-Math, ETH Zürich. (c) A. Cattaneo, Institut fur Mathematik, University of Zurich.

14. United Kingdom: (a) J. Barrett, K. Krasnov, J. Louko, University of Nottingham (b) R. Williams, DAMTP, University of Cambridge. (c) F. Dowker, J. Halliwell, C. Isham, Department of Theoretical Physics, Imperial College, London (d) D. Johnston, B. Schroers, Department of Mathematics, Heriot-Watt University, Edinburgh.

Annex 5

No previous applications to ESF were made.