



**European Cooperation
in Science and Technology
- COST -**

Brussels, 16 December 2010

Secretariat

COST 4189/10

MEMORANDUM OF UNDERSTANDING

Subject : Memorandum of Understanding for the implementation of a European Concerted Research Action designated as COST Action MP1006: Fundamental Problems in Quantum Physics

Delegations will find attached the Memorandum of Understanding for COST Action MP1006 as approved by the COST Committee of Senior Officials (CSO) at its 180th meeting on 1 December 2010.

MEMORANDUM OF UNDERSTANDING
For the implementation of a European Concerted Research Action designated as
COST Action MP1006
FUNDAMENTAL PROBLEMS IN QUANTUM PHYSICS

The Parties to this Memorandum of Understanding, declaring their common intention to participate in the concerted Action referred to above and described in the technical Annex to the Memorandum, have reached the following understanding:

1. The Action will be carried out in accordance with the provisions of document COST 4159/10 “Rules and Procedures for Implementing COST Actions”, or in any new document amending or replacing it, the contents of which the Parties are fully aware of.
2. The main objective of the Action is to address the basic questions in the foundations of quantum mechanics, to develop new advanced mathematical models and to test their physical predictions.
3. The economic dimension of the activities carried out under the Action has been estimated, on the basis of information available during the planning of the Action, at EUR 64 million in 2010 prices.
4. The Memorandum of Understanding will take effect on being accepted by at least five Parties.
5. The Memorandum of Understanding will remain in force for a period of 4 years, calculated from the date of the first meeting of the Management Committee, unless the duration of the Action is modified according to the provisions of Chapter V of the document referred to in Point 1 above.

A. ABSTRACT AND KEYWORDS

"Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing. The theory says a lot, but does not really bring us closer to the secret of the 'Old One.' I, at any rate, am convinced that He is not playing at dice." (*Einstein, 1926*). This view on quantum mechanics is now shared by a large number of scientists spanning the entire spectrum of physics, from pure theoretical analysis to cutting edge experiments.

Europe has the largest number of scientists working on the fundamental problems of quantum mechanics. They see an urgent need to create a common platform to overcome the existing fragmentation. They see the need for unifying their research in a multidisciplinary and coordinated approach, to reach the goal of a full understanding of the quantum world. This COST Action is the first network in the world, focussed on the foundations of quantum mechanics.

The Action aims at strengthening cooperation and boosting research activity among European groups working in the foundations of quantum mechanics. By combining existing research strengths in mathematical, theoretical and experimental physics and quantum chemistry, major breakthroughs in foundational questions will be achieved. The Action will create the necessary platform for enhancing synergies among the participants, exchanging knowhow, coordinating the research and disseminating the results.

Keywords: Quantum Mechanics, Foundations of Quantum Theory, Nonlocality and Entanglement, Decoherence and Open Quantum Systems, Effective Quantum Dynamics.

B. BACKGROUND

B.1 General background

Scientific Background. Quantum mechanics is the most successful physical theory in the history of science. It set out to explain the atomic structure of matter and it has led to revolutionary technologies. Despite the successes, the debate about the precise formulation and the meaning of quantum theory is still raging. In recent decades, the fundamental problems of quantum mechanics have been recognized as urgently important, and are now subject of intense theoretical and experimental research.

The research revolves around four major topics:

1. *Quantum theory without observers.* The motivation for this research was clearly described by J.S. Bell: “The formulations of quantum mechanics that you find in the books involve dividing the world into an observer and an observed, and you are not told where that division comes – on which side of spectacles it comes, for example, or at which end of my optic nerve [...] So you have a theory which is fundamentally ambiguous [...]” (*Bell, 1986*). The aim of research in this area is to resolve the ambiguity by giving a consistent, observer-free formulation of quantum mechanics.
2. *Effective descriptions of complex systems.* The efficient way of describing complex systems is to focus on a few relevant degrees of freedom. The problem is to understand phenomenological laws like the transport of charges, from the underlying microscopic dynamics, which are quantum mechanical. Major advances in quantum chemistry, biology and nanotechnology are based on this analysis.
3. *Quantum theory meets relativity.* After Einstein, our worldview is that of a four-dimensional universe in which the laws of physics obey the principle of relativity. The marriage of relativity and quantum mechanics turns out to be problematic and the existing descriptions of Nature are plagued by infinities. Moreover, Bell’s inequalities proved the nonlocality of Nature, which deepens the tension with relativity. To release this tension is a major open problem in the foundations of quantum mechanics.

4. *From theory to experiments.* “I’m inclined to put my money on the idea that if you push quantum mechanics hard enough it will break down and something else will take over – something we can’t envisage at the moment” (*Nobel laureate A.J. Leggett, 2010*). Bell’s theoretical analysis on quantum nonlocality opened the way to a whole new class of experiments and new quantum technologies like quantum cryptography. In a similar way, the open problems in the foundations of quantum theory are already leading to new cutting-edge experiments testing the validity of the theory, and will give rise to new technological developments.

Strategic Background. Europe has a longstanding tradition and plays a leading role in the foundations of quantum mechanics, and has the largest density of research units working on quantum foundations. Research is done in all the above-mentioned fields. The units are active in scientific collaborations and in organizing conferences and meetings. The research covers theoretical, experimental and mathematical physics as well as quantum chemistry.

In spite of the on-going collaborations, the essential research activity happens within small units and is therefore fragmented, limited by bureaucratic constraints and by a severe lack of global organization. This fragmentation threatens the leading role of Europe in the development of the foundations of quantum physics.

This COST Action will overcome this deficiency. A common platform for research on quantum foundations will be crucial for advancing the field, and increasing the impact of the research of the single units. The Action will create a network in which especially young researchers will find opportunities and support for their future careers when they wish to engage in foundational work.

COST is the most appropriate mechanism as the current fragmentation of research into individual units means that the community requires a period of intense networking before embarking on major new joint research programmes such as those funded by the EU Framework Programme.

B.2 Current state of knowledge

Most foundational research today revolves around four major topics: quantum theories without observers, effective descriptions of quantum systems, quantum theory meets relativity, and experimental verifications of quantum mechanics. The COST Action will be innovative in an attempt to unify and coordinate these foundational research activities.

Quantum theory without observers. At the basis of all foundational problems of quantum mechanics, there is the measurement problem. Quantum mechanics is linear at all scales: hence it implies the existence of macroscopic superpositions (Schrödinger's cat paradox), which are not part of our daily experience. The historical attempt to forbid the emergence of macroscopic superpositions was to assume that an observer collapses the wave function. This however has been since long recognized as an ambiguous ad-hoc remedy. A consistent theory must be observer independent.

There are two major well-developed proposals for quantum mechanics without observers: Bohmian mechanics and collapse models.

In Bohmian mechanics particles exist as discrete objects having positions and moving along trajectories, and deterministic laws govern their motion. The theory is well understood and fully developed for non-relativistic systems. For relativistic systems progress has been achieved, but a complete understanding of a relativistic Bohmian theory remains as an important challenge.

Collapse models encompass theories in which the Schrödinger equation is changed, in order to include the process of wave function collapse in the dynamical laws. These models have become the theoretical toolkit used to inspire ongoing cutting-edge experiments in Europe and elsewhere. Other interpretations of quantum mechanics which need further conceptual and mathematical developments include the many worlds interpretation, the consistent or decoherent histories approach and a more recently proposed approach, quantum measure theory.

Effective descriptions for complex systems. The description of systems containing a great number of particles is simplified by separating relevant degrees of freedom from irrelevant ones. The irrelevant variables are usually summarized either as rapidly varying degrees of freedom, or as a heat bath. The mathematical models thus roughly separate into two groups: the adiabatic approach and the open quantum system approach.

Within the adiabatic approach, the Born-Oppenheimer description of charge transport is the most famous example. In this description, the electrons are treated as the fast degrees of freedom, and the nuclei as the slow, allowing for an approximate solution of the complicated Schrödinger equation of the whole molecular system. Applications of these techniques are in solid-state physics and chemistry.

In the quantum open system approach, the relevant subsystem is singled out, while the remaining part (the surrounding environment) is treated as a bath. The effective dynamics of the subsystem contains a unitary part, reflecting the internal motion, and a non-unitary part, summarizing the interaction with the environment. The success of the open quantum system approach ranges from quantum optics, to nuclear, atomic and molecular physics.

Quantum theory meets relativity. Relativistic field theories, which describe interacting matter, have well-known problems of mathematical consistency, which are usually dealt with by renormalisation procedures. The most famous example of this kind is the point-charge mass renormalisation of electromagnetism. To this set of problems belongs also the description of the apparently simple phenomenon of radiation sent out by an electron while being accelerated, which is also plagued by infinities.

The problem of constructing a physically non-trivial, rigorously defined, interacting relativistic quantum field theory is still open. Dirac called the difficulty in the construction of such a theory a “second class difficulty”, while he called the measurement problem a “first class difficulty”. There are very encouraging attempts to formulate relativistic quantum theories without observers, but no completely satisfactory relativistic quantum theory has been arrived at yet.

From theory to experiments. The debate about the foundations of quantum mechanics has always been accompanied by new experimental tests. The most notable example is Einstein, Podolsky and Rosen's (EPR) criticism of the completeness of the quantum formalism, together with Bell's analysis of Bohmian mechanics, which led to the remarkable discovery that nature is nonlocal, proved experimentally by A. Aspect.

Current experimental analysis focuses primarily on the limits of validity of quantum mechanics, and more specifically on whether the superposition principle holds at large scales. The typical setup is an interferometer, through which large molecules are sent. Efforts are currently being made to increase the size of the molecules from about 3,400 nucleons (present limit), to about 2-3 orders of magnitude more.

Opto-mechanical interferometers represent another promising means to test the superposition principle. These are optical interferometers, at one arm of which a relatively large speck of matter can be placed, which interacts with the bouncing photon. In this way, superpositions of matter can be created, and their quantum behaviour can be tested.

Experiments on Bell's inequalities are still actively being improved upon. Current research focuses on testing entanglement and new Bell-like inequalities for massive systems, in particular neutral kaons. More generally, entanglement and Bell-states are giving rise to a whole new class of experiments and new fields of research: quantum teleportation, quantum cryptography, and quantum information.

In quantum optics, one recent major advance is the creation of entangled Bell-like states containing a large number of photons (about 10,000). Future experiments aim at increasing this number by several orders of magnitude.

A common vision. Scientists working across these four fields share the aim of arriving at a clear and scientifically precise description of the quantum world. They share the conviction that theory and experiments are both essential if we are to revolutionize our understanding of the quantum universe. All the problems are fundamentally linked to each other and researchers share common tools such as certain mathematical techniques. The COST Action provides the umbrella to coordinate the research and give a European dimension to this project.

Innovative aspects. There is no European networking project on the foundations of quantum mechanics. The fragmentation of this research field is not only a European phenomenon, however: it is global and this Action represents an opportunity for Europe to take the lead. The COST Action will bring together scientists from all over Europe to pool their expertise and methods to achieve significant breakthroughs.

For the first time, early-stage researchers (ESRs) will find a platform which enables them to get in contact with and join other leading groups on the foundations of quantum mechanics. Strict applications of gender balance policies will ensure that women scientists working in this field will be well-represented in all Action activities.

The Action will also be used to coordinate an outreach policy to make quantum mechanics in its most fundamental aspects accessible to a wide audience.

B.3 Reasons for the Action

Research on quantum foundations in Europe is scientifically excellent, but at the same time it is fragmented into many research units. Several collaborations exist among these units, but they are not sufficient for coordinating the research on a European scale. The risks of uncoordinated research are the duplication of effort and the missing of opportunities. These barriers to progress can be removed by the formation of a European network based on a shared scientific vision of the major problems that need to be tackled.

This COST Action will counteract fragmentation by creating the first network on the foundations of quantum mechanics in the world. The Action will be built upon the integrated research of the best experimental, theoretical, mathematical physicists and quantum chemists active in Europe. This will lead to more organized research activity, advancing science in a more fruitful and successful way. The Action will provide ESRs with a coordinated environment, where they can successfully work and develop a future career. In view of the growing competition from outside Europe, a common platform where to find expertise, know-how, technologies, working opportunities, is crucial for their career. Appropriate gender balance policies will make sure that equal opportunities will be given to all researchers, supporting in particular women scientists.

A COST Action is the right instrument for facing these new challenges. It will be open to all research units interested in reaching the objectives of the Action, and in the associated research activity.

The expected benefits of the Action include:

- Better organized and more effective research on quantum foundations
- Stronger, long lasting collaborations among scientists
- An integrated platform for ESRs
- A coordinated academic career for young gifted researchers
- More effective dissemination activity to a wide audience
- A more competitive platform for research

Europe has always led the way in quantum foundations, not least because quantum mechanics was mainly developed in Europe. However, in recent years competition from outside Europe, in particular North-America and Australia, has increased considerably. Europe is still leading the field, but without a common network among its research units, it will fall behind other countries, where research on quantum foundations is strongly supported both by public institutions and by private companies. Thus, launching the present COST Action now is timely.

B.4 Complementarity with other research programmes

This Action is absolutely novel for research not only in Europe, but also in the world. Never before have research units, working on the foundations of quantum mechanics, decided to join their efforts and collaborate on a large scale in order to create a common strategic platform.

Several national programmes and bilateral collaborations already fund the research activity on quantum foundations of the single research units. The present Action will now give a European dimension to their research.

Europe has funded several networks and large-scale collaborations on quantum information theory and quantum theories of gravity. The present Action will fill a gap by creating a network complementary to the existing ones, its focus being on quantum foundational problems. Knowledge from this Action will be transferred to and from these other networks via COST Action scientists who have close connections to them.

C. OBJECTIVES AND BENEFITS

C.1 Main/primary objectives

The main objective of the Action is research on the Foundations of Quantum Mechanics.

C.2 Secondary objectives

Objective 1. Coordinate the research activity among units working on fundamental problems in quantum mechanics. Europe hosts a large community of scientists working on foundational problems in quantum mechanics. The community however is fragmented, because of different scientific backgrounds, which originate in mathematics, theoretical and experimental physics and quantum chemistry. A major objective of the present COST Action is to overcome this fragmentation, to boost interactions and collaborations among scientists and units, with benefits for the quality and quantity of the results.

Objective 2. Support and promote gender balance and the involvement of ESRs. The present lack of networking organisation for quantum foundational research in Europe makes it particularly difficult for ESRs to find opportunities for scientific exchange and dissemination of results. With this Action, ESRs will be promoted and trained and at the same time provided with good perspectives for their scientific career. The under-representation of women in physics is exacerbated by the fragmentation of quantum foundations research: there are several women but scattered across the continent and the Action will provide vital opportunities to network with each other. The Action will vigorously promote the participation of women scientists in all Action activities. This will encourage particularly young women scientists who will be able to interact with senior women in their field through Action events.

Objective 3. Promote the dissemination of results, and the interaction with other communities.

We live in the era of information. Exchange and dissemination of results are crucial for coordinating the research among the units, for advancing the field, for interacting with other communities and for being more visible in the global scientific arena. This is crucial also at the political level: namely a problem the quantum foundations community faces is that it is not adequately represented in European scientific policies. Effective dissemination and advertising of the scientific achievements of the community will help make European policies more conscious of the role of foundational physics in the advancement of science.

Objective 4. Organize and prepare applications for future joint training and research projects.

Europe offers several schemes for funding joint activities, like the Initial Training Network (ITN) action, under the Marie-Curie Actions of the VII Framework Programme. Since national funding rarely supports international events and cooperation, European funding programmes acquire a more central role, also because they cover a much larger scale. The Action aims to develop strategies for successfully participating in future funding programmes and for preparing future proposals, in order to give continuity and to build on the scientific success of the Action.

C.3 How will the objectives be achieved?

The objectives of the Action will be achieved through regular meetings, Short-Term Scientific Missions (STSMs), workshops and training schools on quantum foundations, international conferences and knowledge dissemination. More specifically, each objective will be achieved in the following way.

- 1. Coordination of the research activity.** The research activity will be carried out by the individual research units, which possess the necessary facilities, human resources and expertise. These are the best in Europe in the field, and among the best in the world. The COST Action will coordinate the research activity. This will be done primarily through Working Groups (WGs), which will focus on specific topics in quantum foundations, as described in section D.2. They will be responsible for establishing and consolidating collaborations, and for boosting research. The overall coordination will be done through the periodic Management Committee (MC) meetings, workshops, and through the dedicated COST Action website.
- 2. Gender balance and the involvement of ESRs.** The COST Action will offer ESRs excellent opportunities to pursue their research interests, to enhance their training, and promote their careers. The dedicated COST Action website will provide them with all relevant information about the ongoing research activities of the different units, and job offers in quantum foundations. The STSMs will support their mobility among the different units. The planned training schools will provide them with training that cannot be given at the local level. Meetings and workshops will inform them about the most recent research achievements, and will offer them opportunities to present their own results and receive crucial feedback on scientific communication skills from world experts in their field. The objective of promoting the greater representation of women in quantum foundations will be achieved through the policy of mainstreaming of gender balance throughout all Action activities. A Gender Balance Coordinator will ensure that women, both internal to the Action and also external, have opportunities to participate in every meeting, conference and training event.

3. **Dissemination, and interaction with other communities.** Dissemination will be achieved through regular conferences, workshops, scientific publications and reports. These means will also prove the high quality of the research activity of the network. A dedicated website of the COST Action will be set up, where the scientific achievements will be promoted to the quantum foundations community, as well as to other scientific communities and to the general public. A particular effort will be made to make the scientific results accessible to non-experts in the field, in order to promote science to a wider audience; this will be done through the website as well as through articles in magazines and newspapers.
4. **Future joint research projects.** The programmes to apply to, in order to trigger European funding for research in quantum foundations, and the best strategies to adopt, will be discussed during the MC and WG meetings of the Action, and in parallel with the planned conferences.

C.4 Benefits of the Action

1. Scientific benefits for the networking partners. The Action will give each unit the possibility to interact more closely with the other units working in quantum foundations, with significant benefits for the quality and quantity of research activity. Specific benefits will be:

- Development of long-term collaborations.
- Sharing of expertise, scientific techniques, achievements, human resources, and experience.
- Integrating research, ranging from mathematical, to theoretical, to experimental physics, to quantum chemistry.
- Strengthening the units through training of ESRs.
- Formulation of future research programs
- Participation in future joint research programs.

The Action aims to achieve high-profile research results, which will play a fundamental role in a deeper and clearer understanding of the quantum world, and contribute to continuing international recognition of European leadership in quantum foundations.

2. Benefits for ESRs. ESRs will be offered a network, which provides optimal opportunities for strengthening their research careers. Specific benefits will be:

- Acquisition of interdisciplinary competence in their own fields of research and nearby fields.
- Acquisition of interdisciplinary technical skills, ranging from mathematics to experiments.
- Training on foundational programs in physics, by leaders in the field.
- The possibility of collaborating with the most important groups in quantum foundations.
- Updated information about ongoing research, future programmes, job offers.
- Acquisition of self-confidence and of skills necessary to assume team leadership roles in Academic (or Industrial) environments.
- Acquisition of skills in scientific dissemination.

This COST Action aims to prepare well-trained, highly professional, highly competitive, European researchers, ready to take a leading role in future research.

3. Strategic benefits. Europe will have the first integrated network on the foundations of quantum mechanics in the world, which will optimize the scientific activity, will coordinate dissemination, attracting the best researchers and strengthening the leading role of Europe in the field.

4. Benefits for society. Quantum mechanics is basic to mankind's understanding of the universe. It is plagued by mysteries and paradoxes and is certainly one of the most fascinating and attractive areas of science to the general public. The expected results from this Action will give a clearer view of the quantum world contributing to the cultural development of society. This will be promoted through targeted dissemination activities as described in section H.

C.5 Target groups/end users

The first target group, which will benefit from the Action, is that working on **foundational problems in quantum mechanics**. The Action will have a significant impact on the individual members, enhancing their research profile, and the quality of their scientific production.

A second important target group is that of **closely related scientific communities**: the mathematical physics community, the solid-state physics community and the experimental physics community.

A very relevant target group is that of **ESRs**, who represent the future generation of scientists. Among them, special attention will be given to **women students and young researchers**, in order to increase the number of women scientists working in the foundations of quantum mechanics. Specific actions to support gender balance and the involvement of ESRs are described in section E.4.

Another important target group will be the **general public**. Through the dedicated COST Action website, a particular effort will be made to explain quantum mechanics, its conceptual problems, the recent achievements, the technological developments, to as wide an audience as possible. The goal is to promote the importance of science, and in particular of the scientific policies adopted in Europe, for society and its future.

D. SCIENTIFIC PROGRAMME

D.1 Scientific focus

Since the beginning of quantum mechanics, there has been the feeling that the theory is very powerful but also, at the same time, very mysterious. There is the feeling that the theory captures a deep truth about Nature, but in a way that seems paradoxical and provisional. Therefore the quest to understand the quantum universe is considered to be urgent by an ever-increasing number of scientists.

The Action is the instrument which, for the first time, will enable scientists working in the foundations of quantum mechanics to coordinate their research. In this way they will overcome the present fragmentation of research activities by creating a network on a European scale, which aims at leading this field of research worldwide.

Reflecting the topics described in section B.1 and B.2, four complementary Working Groups (WGs) will be established. They cover the most important issues in the foundations of quantum mechanics. They are naturally intertwined, both by sharing the common aim of clarifying the deep-lying mysteries of quantum mechanics, and by sharing similar theoretical and experimental techniques to reach this goal. Most researchers will find themselves represented by more than one WG. The WGs, and the relative tasks, are organized as follows.

WG1: Quantum theory without observers. The measurement problem (Schrödinger's cat paradox) is a fundamental problem in quantum mechanics. There is a wide variety of proposed solutions, such as the many worlds interpretation, consistent histories, Bohmian mechanics, collapse models, quantum measure theory, quantum logic and the Copenhagen interpretation. There is no consensus among scientists about which approach is more promising. A primary task is to come to a consensus on the status of the measurement problem and of the proposed solutions. Other relevant tasks include:

- The proposed solutions of the measurement problem have reached different degrees of mathematical development. Further development is necessary in order for them to become comparable and competitive descriptions of the quantum world.
- Collapse models make predictions, which differ from those of quantum mechanics. An important goal is to analyze the most promising physical situations where such differences can be tested. This will lead to cutting edge experiments challenging quantum mechanics and which may discriminate between the proposed solutions.
- One of the mysteries of quantum mechanics is how to describe measurements of time, for example the time it takes for a particle to tunnel through a barrier. Bohmian mechanics provides a clear description of measurements of time. Applications to experimental situations will be analyzed.

WG2: Effective descriptions of complex systems. The general task is to achieve a clear mathematical picture of how phenomenological descriptions of complex systems emerge from the underlying quantum laws. To give an example from a currently hot topic, with the advent of spectroscopic techniques that monitor chemical and biochemical processes on the femtosecond scale, it has become increasingly clear that many elementary molecular processes tend to preserve their coherent quantum character when coupled to an environment. This holds for both simple environments, like solvents, and complex ones, like protein pockets. Recent experiments suggest that excitonic coherence plays a key role in photosynthetic antenna systems. Thus the conventional picture of emergent macroscopic features does not necessarily hold on the time and length scales that are decisive for chemical and biological function. Other relevant tasks include:

- The boundary between quantum and classical behaviour, for example in molecular systems, is fuzzy and subject to debate. To probe the classical versus the quantum domains is a primary foundational issue with far reaching practical consequences.
- The phenomenon of decoherence and dissipation is well understood in general terms but specific aspects and their influences in particular physical or chemical situations need to be further worked out, for example towards the non-Markovian regime.
- The quantum dynamics of energy and charge transfer in extended systems, in particular biomimetic and nanostructured systems, e.g. arrays composed of quantum dots, carbon nanotubes, or porphyrin molecules, is not fully understood and needs further analysis.

WG3: Quantum theory meets relativity. Relativistic quantum mechanics is the foundation of our understanding of matter. To construct a mathematically consistent relativistic theory of Nature is one of the most difficult problems in theoretical physics. The reasons for that are many, but the tension between relativity and quantum nonlocality plays a central role, which has not been fully scrutinized. This tension enhances the difficulty of the measurement problem.

- A primary task is to formulate a relativistic quantum theory without observers, i.e. a theory where the collapse of the wave function follows from the fundamental equations, which are relativistic.
- A secondary task concerns the clarification of renormalisation rules within relativistic quantum mechanics.

WG4: From theory to experiment. In natural sciences, experimental verification and theoretical analysis are intimately intertwined. In quantum mechanics a new class of cutting edge experiments will soon challenge the validity of the theory. Theoretical analysis is needed to find the proper focus for such experiments. Tasks include

- Perform a novel class of time measurements in quantum mechanics, which include time-of-flight and tunnelling-time measurements; compare the results with theoretical analysis.
- Improve current matter-interferometric experiments (with macro-molecules) and opto-mechanical experiments, and devise new experiments, in order to test the validity of the linearity of quantum mechanics towards macroscopic scales.
- Refine tests of quantum nonlocality, in particular for massive entangled systems (kaons, atoms).

The research units, which have already agreed to join the Action, will carry out the research programme, together with other units, which will decide to join in the future. All necessary facilities are provided by the Universities and Scientific Institutions, to which the units belong. The cost of the Personnel will be covered by the Universities/Institutions, as well as by national funding schemes.

D.2 Scientific work plan methods and means

The scientific work plan will be organized in four Working Groups (WGs), which reflect the four general topics described in section B.1 and B.2. They are responsible for carrying out the scientific research listed in section D.1, as well as for coordinating the research activity of the research units taking part to each WG. The WGs are intertwined, and interdisciplinary communication is supported as an important means to achieving outstanding results. Due to the universal character of the foundational issues to be addressed, the WGs are necessary organizational units to achieve highly specialised and focussed results, which in total contribute to the common objective to solidify foundational research in Europe.

WG1: Quantum theories without observers. The aim is to develop and further analyze alternative formulations of quantum mechanics, where observers play no fundamental role, and where the collapse of the wave function and the whole phenomenology of ‘quantum measurements’ derive entirely from the dynamics.

The scientific work plan will include:

- Understand quantum mechanical scattering from first principles.
- Clarify the role of decoherence on the motion of Bohmian particles, leading eventually to classicality.
- Analyze the statistics for experimental outcomes in experiments that measure time, e.g. tunnelling times and arrival times based on typicality.
- Advance the understanding of topological effects in quantum mechanics.
- Develop an appropriate measurement formalism for collapse theories.
- Analyze the most promising, experimentally testable deviations from quantum mechanics.
- Develop collapse models with non-Markovian and/or dissipative effects.
- Further analyze models where the collapse is induced by gravity.
- Develop Quantum Measure Theory.

Methods and means to achieve the objectives.

- Develop refined and adapted mathematical tools; in particular, establish smoothness properties of generalised eigenfunctions. Establish good numerical methods to analyse numerically time of flight or tunnelling times for Bohmian trajectories. Establish the classical limit of Bohmian mechanics for a large class of wave functions invoking the effect of decoherence using multi scale analysis, separating decoherence and dissipation. Develop the mathematical tools to explain topological effects in Bohmian mechanics.

- Describe the statistics of the experimental results in collapse models by positive operator valued measures. Analyze the most promising situations where the predictions of collapse models differ most significantly from those of standard quantum mechanics. Extend the dynamical equations describing the process of wave function collapse, by including dissipative terms (in order to restore the principle of energy conservation) and non-Markovian terms (in order to consider collapsing fields with general spectra).
- Show that the path integral gives rise to a vector-valued measure on the algebra of elementary events for which an extension theorem for measures can be applied. This will allow an extension theorem to be employed, given certain conditions on the measure. Previous work suggests that the dynamics of quantum mechanics will have to be modified by introducing a high energy cut-off in order for the conditions on the measure to be satisfied.

WG2: Effective descriptions of complex systems. The aim is to develop more refined effective descriptions of complex quantum systems, starting from the underlying equations of quantum mechanics.

The scientific work plan will include:

- Find effective equations for relevant degrees of freedom in a complex system. These include weak coupling limits, effects of decoherence, dissipation, and macroscopic constraints.
- Develop the theory of non-Markovian descriptions for open quantum systems.
- Find good algorithms to solve non-Markovian master equations.
- Further analysis of the effect of interactions on quantum phenomena, which are linked to entanglement, interference and decoherence.
- Understand the role of coherence in transport phenomena in chemical and biological systems.
- Find good algorithms to solve the time dependent Schrödinger equation for many particle systems.

Methods and means to achieve the objectives.

- Development and application of multi-scale analysis. Development and application of geometrical methods adapted to wave function transport, which can be dynamical or geometrical. Work out models of systems coupled to a heat bath, or fast degrees of freedom, which allow for a short term memory description of the reduced dynamics.
- Understand the range of applicability of Markovian limits as compared to non Markovian dynamics.
- Development of the theory of non-Markovian dynamics and of a notion of typicality for such evolutions. Creation of a general fundamental framework within which phenomenological Ansätze can be considered which avoid previous unphysical results. Both advanced mathematical and numerical techniques will be needed.
- Study of hybrid models which couple quantum systems to classical environments. Study of particular models with nanostructure like arrays composed of quantum dots, carbon nanotubes, or porphyrin molecule. For better understanding of diffraction and interference effects, study particular models like the van der Pol differential equation with added noise or the Caldeira-Leggett Hamiltonian and the Cardirola-Kanai Hamiltonian.
- Combine the study of open quantum systems with the specific characteristics of quantum theories without observers.
- Develop further Bohmian grid methods for numerical solutions of the time dependent Schrödinger equation to be applied in time statistics, chemical reactions and biological processes.

WG3: Quantum theory meets relativity. The aim is to understand and to ease the tension that exists between the nonlocality of quantum mechanics and the local character of relativity.

The scientific work plan will include:

- Construction of relativistic versions of Bohmian mechanics
- Further development of Lorentz-invariant collapse theories.

- Generalization to interacting theories, in particular gauge theories.
- Clarification of regularisation procedures in quantum field theory on the basis of quantum theories without observers.
- Clarification of the unification of gravity and quantum physics.
- Statistical analysis of quantum theory without observers in relativistic physics.

Methods and means to achieve the objectives.

- The construction of Bohmian theories needs a foliation of space time which may or may not destroy relativity. Covariant foliations are possible and need to be further scrutinized. Relativistic space time symmetry may also appear on the macroscopic scale, while the fundamental theory has a different symmetry. A similar phenomenon is well known from the appearance of irreversible macroscopic evolutions while the fundamental evolution law is time symmetric. The underlying statistical analysis based on a notion of typicality needs to be developed and discussed. Possible experimental effects like detection of preferred frames will be studied. The introduction of realistic fields or particle positions for quantum field theory needs regularity properties of the quantum field theory which must be analysed. If needed, modifications of quantum field theory will be introduced and their consequences analysed.
- The possible interplay between gravitation and collapse theories will be further explored. Particular attention will be given to the analysis of possible experimental confirmation.
- In trying to merge collapse models with special relativity, two approaches will be followed. One is to find a genuinely stochastically Lorentz-invariant theory of spontaneous wave function collapse. This has been done recently for the case of free particles, the extension to interacting particles is still missing. The other approach is to assume that the field causing the collapse of the wave function selects a preferred reference frame, and breaks Lorentz invariance at the phenomenological level. Both approaches will be investigated.

WG4: From theory to experiments. The aim is to test the fundamental properties of quantum mechanics. Among them are: nonlocality experiments, tests of quantum linearity, measurements of time.

The scientific work plan will include:

- Realisation of novel time measurements in quantum mechanics, which measure tunnelling time, arrival time, time-of-flight for quantum systems. Existing theoretical formulas will be compared with experimental outcomes.
- Novel Bell-type experiments of quantum nonlocality involving massive particles, such as neutral kaons and atoms.
- Improved tests of the superposition principle, by means of interference and diffraction experiments with macro-molecules and opto-mechanical interferometers.

Methods and means to achieve the objectives.

- Achieve experimentally good control on single particle wave functions or on Bose-Einstein-condensates, in order to measure the time-of-flight, tunnelling times and arrival times of quantum systems. Prepare the theoretical background.
- New Bell-type inequalities can be tested with massive particles. This is novel since the usual experiments involve photons. The best candidate particles are meson-antimeson systems, which are copiously created in accelerator facilities designed for precision measurements for quantities such as CP violation. E.g. the DAPHNE machine in Frascati (Italy) or the KEK machine near to Tokyo (Japan) are currently upgrading and the machines themselves are better and better understood. Such laboratories also represent the ideal set up for testing Bell-type inequalities – and thus quantum nonlocality – in matter.

- Testing quantum linearity at larger scales is a great scientific challenge. Working with more massive molecules means dealing with larger objects and shorter wavelength. The first difficulty is that the slits of a solid grating are too small for the molecule to pass through. This problem can be circumvented by replacing solid gratings with light gratings. A second problem is environmental decoherence, which tends to increase with the size of the system. A third problem is to keep the initial velocity distribution of the molecules sharp enough. All these effects tend to spoil the final interference pattern. Experiments will be done to improve all these aspects.
- A novel approach to testing the superposition principle of quantum mechanics, is to consider opto-mechanical interferometers, where a tiny mirror is mounted on a cantilever in one of the two arms of the interferometer. A photon in a superposition of travelling through both arms, puts the mirror in the superposition of oscillating and being at rest: in this way a superposition of two spatially separated states of the mirror is created. The visibility of the outgoing photon measures the coherence of the superposition of the two states of the mirror. The advantage of such an approach is that the mirror can be relatively big (about 10^{14} atoms); the disadvantage is that the distance between the two terms of the superposition is very small (about 10^{-11} cm). The main difficulty is keeping the whole system isolated from environmental decoherence. At present, the main goal is to have a good control of the system, away from sources of noise.

The mathematical tools to achieve the objectives are common to all WGs. Together with the common goal of understanding the foundations of quantum mechanics, they guarantee unity to the Action. These tools include advanced functional analytic methods, stochastic differential equations, path integral methods, differential geometric methods and refined numerical methods.

E. ORGANISATION

E.1 Coordination and organisation

The organization of the Action will conform to the document: “Rules and procedures for implementing COST Actions”.

Four aspects will be given particular attention: management, scientific coordination, dissemination, gender balance and involvement of ESRs.

1. Management.

Management Committee: A Management Committee (MC) will be established to properly represent the Countries joining the Action. It will supervise and coordinate the implementation of the COST Action, and ensure that the milestones are accomplished. It will meet twice a year, to discuss the achievements and the problems encountered; it will plan future activities, and will convene for additional meetings if any special need arises. It will report to the COST office on a yearly basis.

Core Group: A core group (CG) of the MC will be nominated to assure more rapid, efficient and flexible coordination of the Action. The CG will be formed by the MC Chair, the MC vice-Chair, the WG Leaders, by the STSMs manager, and by the Gender Balance Coordinator. The CG will prepare all relevant documents (scientific, orientation, etc) for the MC meetings.

Kick-off Meeting: During the Kick-off Meeting, once the Chair and Vice-chair have been elected, the MC will proceed with the basic organization of the Action: establishing the Working Groups and appointing their Leaders; establishing the Core Group; nominating the STSMs Manager, the Gender Balance Coordinator and the Grant Holder; setting basis rules for organizing the implementation of the Action; introducing collaborative tools.

Working Groups (WG): Each WG will be chaired by a WG Leader. A vice-Chair will be also appointed. They are selected by, and report to the MC. They will be responsible for the management of the implementation of the Action Working Plan. They will coordinate the progress and technical work under each WG. They will report to the CG.

STSMs Manager: He/She will coordinate the STSMs. He/She will be responsible of overseeing the STSM-implementation plan, prepare the selection and review process of the annual STSMs. Decisions will be taken by the CG and reported to the MC.

Gender Balance Coordinator (GBC): He/She will have responsibility for mainstreaming gender balance throughout all Action activities, for example invitations to speak at Action meetings and conferences, and will oversee the mentoring scheme. He/She will report to the CG on the proportion of women participating at conferences and training events and on the efforts to increase participation by women. He/She will coordinate the Mentoring Scheme for women scientists.

2. Scientific coordination. The scientific activity will be organized in four Working Groups (WGs). WG meetings will be organized twice a year, where also the main topics for workshops and themes for the international conferences will be discussed. The main coordination tasks will be:

- Promote scientific collaborations, the exchange of knowledge, human resources and expertise.
- Contribute to the organization of the planned training schools, workshops, and conferences.
- Contribute to the dissemination activity of the Action, providing the scientific content for the COST Action website.
- Promote the participation of the research groups in future joint European programmes.

Workshops on specific topics related to the Scientific Workplan of the Action, will be organized on a regular basis. Members of different WGs, when working in nearby fields, will be invited to participate in these workshops.

3. Dissemination. Coordinated dissemination is a fundamental component of the Action. The dissemination plan is described in section H.

4. Gender balance and involvement of ESRs. The Action strongly supports gender balance and the involvement of ESRs. Specific actions and activities are described in section E.4.

Deliverables and milestones.

Year	Milestones	Deliverables
1	<p>Month 0 Kick off meeting: MC is set up; Work Plan is established; Call for Training School 1</p> <p>Month 6 MC meeting 1; WG meetings; Workshop 1; Decision on Training School 1; Call for International Conference 1; Launch of Mentoring Scheme</p> <p>Month 12 MC meeting 2; WG meetings; Workshop 2; Organization of International Conference 1; Call for Training School 2; Discussion about the best dissemination activities</p>	<p>Web site fully operational WGs reports Annual Report Scientific report (publications, ...) STSM report Mentoring Scheme set up Training School 1 Workshop1 Workshop2 Outreach Activities</p>
2	<p>Month 18 MC meeting 3; WG meetings; Decision on Training School 2; International conference 1.</p> <p>Month 24 MC meeting 4; WG meetings; Call for Training School 3; Review the scientific strategies; Review of the dissemination activity; Workshop 3</p>	<p>WGs reports Annual Report Scientific report STSM report Report on gender balance and mentoring Overview of the plans Training School 2 International Conference 1 Workshop3 Outreach Activities</p>

3	<p>Month 30 MC meeting 5; WG meetings; Decision on Training School 3; Call for International Conference 2; Workshop 4</p> <p>Month 36 MC meeting 6; WG meetings; Workshop 5; Organization of International Conference 2; Call for Training School 4; Review of the dissemination activity; strategies for the future</p>	<p>WGs reports Annual Report Scientific report STSM report Report on gender balance and mentoring Training School 3 Workshop 4 Workshop 5 Outreach Activities</p>
4	<p>Month 42 MC meeting 7; WG meetings; Decision on training school 4; International Conference 2</p> <p>Month 48 MC meeting 8; WG meetings; Workshop 6; Final reports and strategies for the future</p>	<p>WGs reports Final Reports Scientific report STSM report Assessment of Gender Balance activities. Training School 4 International Conference 2 Proceedings of International Conference Workshop 6 Outreach Activities</p>

E.2 Working Groups

The Management Committee (MC) will set up four Working Groups (WGs).

WG1: Quantum Theories without observers

WG2: Effective descriptions of complex systems

WG3: Quantum theory meets relativity

WG4: From theory to experiment

These WGs reflect the four major areas in which research on quantum foundations can be naturally grouped. They also reflect the common desire to arrive at clear and mathematically precise description of the quantum world, solving the fundamental difficulties that still plague quantum mechanics. On the more technical level, the WGs are intertwined in the following way:

- WG1 and WG2 focus on the transition from microscopic quantum physics to macroscopic classical dynamics. In doing this, they share similar mathematical techniques, like stochastic processes and method of functional analysis.
- WG1 and WG3 both aim at setting quantum mechanics (whether relativistic or not) on a firm mathematical basis, by working on its mathematical foundations and on the same paradoxical aspects of the theory.
- WG2 and WG3 share common mathematical tools, like path integration methods and methods of functional analysis.
- WG4 represents the experimental counterpart to the theoretical analysis of WG1-WG3, thus it is intimately connected to them.

This interconnection mirrors the fact that most units are active in research topics pertaining to more than one WG. Therefore WGs will have regular intergroup communications. The existing cross-links between the WGs will increase during the course of the Action's duration, maximising the impact of the Action.

E.3 Liaison and interaction with other research programmes

All groups, which have already accepted to join the Action, have ongoing collaborations with other high ranking scientific institutions, both inside and outside Europe. These collaborations are supported by

- Joint research activities
- Staff exchange
- Bilateral research agreements
- Organization of joint workshops and conferences

One objective of the Action (as described in section C.2) is also to promote the participation of its members in future research programmes, in particular those launched within the European Framework Programmes.

E.4 Gender balance and involvement of ESRs

This COST Action will respect an appropriate gender balance in all its activities and the MC will place this as a standard item on all its MC agendas. The Action will also be committed to considerably involve ESRs. This item will also be placed as a standard item on all MC agendas.

The Gender Balance Coordinator has responsibility for all policies on gender balance. Already at the level of single units, gender balance is promoted by local equal opportunities. Within the COST Action, the on-site activities of each unit will be assembled and published on the internal website as a best-practice guideline.

The COST Action will also benefit women in the following ways:

1. *Role models*: Amongst the participants of this COST Action, there are several established women scientists. Their profiles will be raised by participation in the Action and they will serve as role models for younger women scientists inside and outside the COST network.
2. *Mentoring Programme*: A mentoring programme will be coordinated by the Gender Balance Coordinator (GBC). Senior members of the COST network will offer one-to-one mentoring to women scientists in the network who would like the opportunity to receive career advice and coaching. The senior scientists will not necessarily be women since the burden of mentoring should not fall solely on the senior women but the senior women in the network will be strongly encouraged to participate. A young woman in a research unit without a senior woman scientist could benefit hugely from contact with a senior woman in the network.

3. The Action will encourage women scientists to take concrete responsibilities and duties within the Action, especially those with a high visibility profile. The Action will also promote their participation to all scientific activities, both internal and external. The GBC will supervise and coordinate the involvement of women scientists in all the activities. The Action is committed to specific measures aimed at increasing the number of women scientists working on quantum foundations.

The Action will also be committed to providing substantial support to ESRs. Training and proper support in the early stages of their scientific career is fundamental for the advancement of the field. For these reasons, their involvement is one of the main objectives of the Action, as described in section C.2.

All participating units are already actively involved in training ESRs. It is the firm aim of the participants of this Action to coach the ESRs by the following means:

1. *“Learning on the job”*: Collaboration between experienced researchers and ESRs at all levels, including devolving management tasks and outreach activities to ESRs, will be strongly supported.
2. *WG*: The participation of ESRs in the WG meetings, workshops and conferences will be promoted.
3. *Training Schools*: Training schools on specific topics will be organized every year. They will train ESRs on the current research activities, on the open problems and on the most advanced mathematical and computational techniques. Team leaders will favour the invitation of ESRs to present communications and participate in their organization.
4. *STSMs*: STSMs will focus on promoting the mobility of ESRs. They will also provide an excellent platform for broadening the scientific horizon, learning new technical aspects, creating new collaborations and experiencing different working environments through visits and secondments.

F. TIMETABLE

The Action will be executed over four years – an interim timetable is shown below. Due to the nature of the open and flexible framework of this Action, a re-adjustment of the scientific and organisational activities may become necessary. These required changes will be identified by the MC and performed by the CG.

Activity	Year 1				Year 2				Year 3				Year 4			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
WG1	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
WG2	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
WG3	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
WG4	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Other Activities																
Kick off meeting	•															
Establish MC, CG, WGs	•															
Definition of work plan	•															
Set up of Website		•														
MC/WG meetings		•		•		•		•		•		•		•		•
Workshop		•		•				•		•		•				•
Training school			•				•				•				•	
International conference						•								•		
Mentoring Programme			•	•	•	•	•	•	•	•	•	•	•	•	•	•
Outreach Activities			•	•	•	•	•	•	•	•	•	•	•	•	•	•

G. ECONOMIC DIMENSION

The following COST countries have actively participated in the preparation of the Action or otherwise indicated their interest: AT, BE, CH, DE, ES, FI, FR, HR, HU, IL, IT, NL, PL, SE, SK, UK. On the basis of national estimates, the economic dimension of the activities to be carried out under the Action has been estimated at 64 Million € for the total duration of the Action. This estimate is valid under the assumption that all the countries mentioned above but no other countries will participate in the Action. Any departure from this will change the total cost accordingly.

H. DISSEMINATION PLAN

H.1 Who?

The MC will be responsible for and will oversee the Outreach and Dissemination Strategy of the Action and will direct the dissemination activities for the different target groups. The dissemination material will be adapted to the needs of these specific groups.

The dissemination addresses two main target audience groups, internal and external. The internal group includes:

- Scientists working in the research units which join the Action
- PhD Students
- ESRs interested in quantum foundations
- Women scientists interested in quantum foundations.
- The external group includes:
 - Other researchers, young researchers, and students
 - Universities/Research Institutions/Academies
 - Opinion formers, European-level and regional-level Research Policy decision-makers
 - National and European Funding agencies
 - Media: scientific and non-scientific press, digital media and TV
 - Other European Cooperation projects, Networks of Excellence
 - General public

H.2 What?

The dissemination plan is designed to achieve maximum transfer of knowledge within the network of units joining the Action, and outside it. The methods will be chosen depending on the target audience, and include:

1. A **dedicated Website** of the COST Action. It will be set up with three level of access:
 - *Password-protected level.* This access-level will allow private information exchange about available facilities and work in progress for members of this COST Action only. It will contain information about MC meetings, scientific reports, non technical interim and annual reports, STSM reports, financial reports, working papers, guidelines and manuals.
 - *Publically accessible level (for scientists).* The public area will allow broad dissemination of the Action outcomes in form of common scientific publication database and information on past and upcoming events. This will contain information about the management structure, contact points and activities of the Action, including conferences, workshops, training schools, training events (both within the network and worldwide), a list of potential host groups for technical visits and training. Links to publications and articles in scientific and technical journals, proceedings, job opportunities, project opportunities, PhD and MSc studentships will also be available.
 - *Publically accessible level (general public).* Quantum mechanics is the subject of many popular scientific books, which, due to the lack of scientific consensus, often offer an inadequate presentation of the main conceptual issues in the foundations of the theory. The COST Action attaches great importance to the accurate dissemination of science to the widest audience. This area of the website will provide accurate, up to date information about quantum foundations, the main problems, the provisional solutions and the future of the subject in an accessible format.

1. **Electronic mail distribution lists** and forums.

2. **Regular meetings.** These include workshops organized by the MC, together with other international scientific events.
3. **Two international conferences** on “fundamental problems in quantum physics” will be organized, to promote the research activity of the network.
4. **Regular exchange of researchers** within the network and outside it.
5. **Training schools** and training events, as well as lectures by leading scientists in the field.
6. **Technical scientific publications:** articles in peer-reviewed scientific and technical journals, reports, proceedings.
7. **Technical documents:** guidelines, manuals, interim and final reports.
8. **Non technical publications:** press briefings and releases for the general public.

H.3 How?

The dissemination of results will be achieved by the following methods:

1. The dedicated **website** will be a vital dissemination point, which will be addressed to the members of the network, to other scientific communities, to general audience. It will provide information about the Action, its structure, its members (title, affiliation, addresses, email, short CV), as well as its activities including conferences, workshops and training schools. It will also post information about publications, articles and technical journals, proceedings, job opportunities, project opportunities, PhD and MSc studentships. It will provide access to scientific, interim and annual reports, case study and STSM reports, financial reports, working papers, guidelines and manuals.
2. **Workshops, seminars and conferences** organised by the MC will be a second important route for dissemination. They will bring together researchers for discussion of the progress achieved to date. The MC will encourage and invite scientists not directly involved in this COST Action to take part in these events.
3. **Mailing lists** for the committees and members of WGs will allow coordination and information exchange at each level.

4. **Training schools** and training events, as well as lectures given by leading scientists, will enable dissemination primarily to ESRs and PhD students. Training in advanced techniques of science communication will be included in the training activities targeting ESRs.
 5. **Scientific Retreat:** Although Internet communication tools are available for all partners, the Action will further promote cooperation between partners with the use of a scientific retreat, creating a distraction free environment allowing intensive discussion, debate and brainstorming. The retreat will be used as a tool for the network, creating space/time for participants to plan collaborative experiments, write joint papers and grant applications together.
 6. **Non-technical articles**, press releases and invitations for media exposure (when appropriate) will contribute to dissemination to the general public.
 7. **Technical documents and reports** will bring the community working on quantum foundations to the attention of European and regional level Research Policy decision-makers.
 8. Subject to copyright and licensing arrangements, a copy of **publications** arising from and supported by this COST Action (including journal articles, books and conference and workshop proceedings) will be deposited in the e-print repository of the COST Office.
 9. The **Final Evaluation Report** will cover the dissemination and exploitation of the results in line with the DC's Terms of Reference.
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