ANNEX I

LIST OF PARTICIPANTS AND DESCRIPTION OF WORK

Network Title: Quantum Complex Systems: Entanglement and Decoherence from Nano- to Macro-Scales.

Network Short Title: QUACS.

Part A - The Participants

The Principal Contractor and the Members listed below shall be jointly and severally liable in the execution of work defined in part B of this annex:

The Principal Contractor

1. The Weizmann Institute of Science **[Weizmann]** established in Israel.

The Members

2. Institut fuer Experimentalphysik der Universitaet Wien **[Vienna]** established in Austria.
3. Universitaet Kaiserslautern **[Kaiserslautern]** established in Germany.
4. Centre National de la Recherche Scientifique **[Orsay-CNRS]** established in France.
5. Kungl. Tekniska Högskolan **[Stockholm]** established in Sweden.
6. Technische Universitaet Berlin **[Berlin]** established in Germany.
7. Istituto Nazionale per la Fisica della Materia **[Naples-INFM]** established in Italy.

Part B - The Joint Programme of Work

1 Project Objectives

The largely unexplored domain of interference, entanglement and decoherence in *Quantum Complex Systems* (QUACS), namely, molecular, quasimolecular and condensed media, will be researched by the Participants. The unifying themes of the network are: (a) interferometric and probe-scattering characteristics of matter waves and their entanglement in QUACS and the hampering of these characteristics by decoherence; (b) active control of decoherence and entanglement in QUACS by electromagnetic (EM) fields. Progress along these lines will be accomplished by collaborative experimental-theoretical studies striving towards the following objectives:

Objective A. Theoretical and Diagnostic Approaches to Entanglement and Decoherence in QUACS: **A1) Dynamical approach to entanglement and decoherence:** The sought novel approach to decoherence will consist in dynamically analysing the evolution of *information (QI) flow* between the system and its reservoir, allowing for the *correlation ("memory") time or spectral response* of the reservoir. **A2) Characteristics of internally-translationally entangled wavepackets:** The network will study *the propagation of such wavepackets, their information flow* and its redistribution when two such wavepackets become *entangled by various mechanisms* (see Objective D).

Objective B. Development of Matter-Wave Interferometry for QUACS: Experimental and theoretical investigations of innovative interferometers for matter waves of complex systems will be the focus of this objective. It will encompass: **B1)** a laser-based interferometer for molecular dimers; **B2)** an interferometer for macromolecules; **B3)** mesoscopic and superconducting solid-state interferometers (for charged quasiparticles or Cooper pairs). These studies will strive for the ultimate goal of *matter-wave interference with controlled entanglement of internal and external (translational)* states.

Objective C. Probe Correlations in QUACS and their Implications: The network will undertake to *characterize the probe-scattering spectra and their statistical correlations for bi-particle or multiparticle systems.* This theoretical analysis will help to interpret the *sub-femtosecond probing of proton entanglement* effects under ambient conditions in molecular and other condensed media, primarily by neutron scattering. In particular, the possibility of proton entanglement effects in biologically or biochemically active substances will be investigated.

Objective D. Strategies for Manipulating Decoherence and Entanglement in QUACS: A collaborative effort involving *most partner teams* will consist in theoretically developing and experimentally implementing new manipulation strategies, based on appropriately designed EM control fields. Two goals will be pursued in this context. **D1) Entanglement "engineering":** The network will consider how to construct the desired entangled state of a given QUACS via Hamiltonian control. **D2) Decoherence control:** This goal will be pursued via frequent measurements or field-induced AC-Stark modulation of the system-reservoir coupling, so as to yield either the acceleration or the inhibition of decoherence.

2 Research Methods

A. Theoretical Methods (Stockholm, Orsay, Weizmann, Vienna):
For *multi-level* systems and *internally-translationally entangled* wavepackets coupled to *arbitrary* reservoirs, numerical or approximated solutions of coupled non-Markovian equations will yield the *decoherence and adiabatic time scales* for the pertinent observables. These solutions and the space-time dependent flow of QI will serve to analyse the transition from unitarity to classicality.

B.1. Laser-Based Interferometry of Dimers and Entanglement. (i) The **Kaiserslautern** group will use a high-vacuum molecular beam and develop laser-frequency stabilization, aimed at achieving long coherence times, in order to implement STIRAP-based matter-wave mirrors and beam splitters for dimers. These elements will subsequently be combined into a molecular matter-wave interferometer. (ii) Feasibility studies of entangling pairs of molecules will attempt to replace the coherent pump laser in the STIRAP-based beam splitter by a quantized mode of a moderate-Q resonator externally driven by an optical parametric oscillator (OPO). (iii) The feasibility of transfering entanglement from dissociated molecular fragments to two photons in high-Q cavities or to correlated light beams will be examined (**Weizmann, Kaiserslautern**). (iv) The feasibility of preparing entangled dimer states using field-induced interactions will be investigated.

B.2. Interferometry of Polyatomic Molecules. The experiments planned in **Vienna** will be aimed at developing novel sources of slow (thermo-labile) molecules in internally-cold states. Part of the studies will recur to the laser desorption techniques of mass spectroscopy, but with neutral rather than charged particles. Methods of coherent field-induced interferometry (beam-splitters and interferometers) will also be explored, with help from **Kaiserslautern**. The use of lithographic gratings will be explored. Controlled coupling to the environment will permit to study the operational QI flow and possible internal-translational molecular correlations (with **Orsay, Weizmann**).

B.3. Interferometry in Superconducting and Mesoscopic Structures. The **Weizmann (experimental)** group will develop new high-visibility electron interferometers. These interferometers will be used to test effects of controlled dephasing of correlated mesoscopic systems ("which path" experiments). The possibility of electron entanglement in superconducting and/or mesoscopic structures will be sought (by **Weizmann/Delft, Vienna and Naples**).

C. Proton Entanglement in Condensed Media. Most of the **Berlin** experiments (in partial cooperation with the subcontractors **Uppsala** and **ISIS**) will employ the neutron Compton scattering (NCS) technique. These experiments will be mostly performed at the **ISIS** facility, UK. Their analysis (with help from **Orsay, Weizmann and Vienna**) will search for possible effects of decoherence and entanglement in various environments.

D. Entanglement and Decoherence Control. D1. Electromagnetic fields and field-induced interactions will be investigated as a means of *entanglement* and *decoherence control* of multilevel or multi-atom systems and internally-translationally entangled (atomic or molecular) wavepackets **(Orsay, Weizmann, Vienna). D2.** Non-holonomic control of Rydberg dimer states by RF variation of the Stark field will be attempted **(Orsay). D3.** The **Naples** group will work on the novel high-T_C superconductivity (HTS) π-junctions, striving for reduction of decoherence in π-junction loops. **D4.** Feasibility studies of circuits comprised of π-junction loops and/or semiconductor mesoscopic structures will be oriented towards entanglement and decoherence control (**Naples, Stockholm, Weizmann/Delft**).

The chart below (Fig. 1) indicates the topical structure of collaboration within the network.

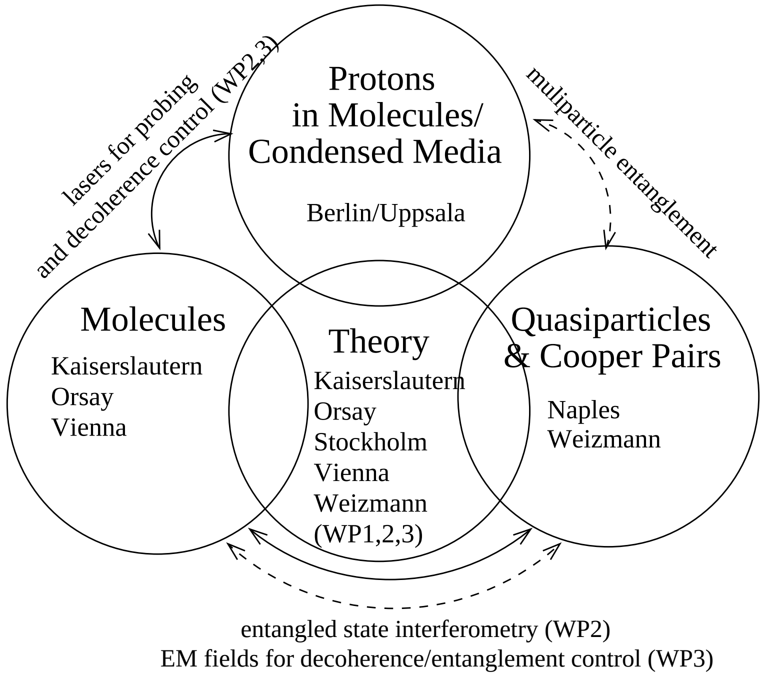

Figure 1: Structure of collaboration within the network.

3 Work Plan

• Schedule and Milestones

Notes: (a) The three workpackages (WP) are divided into specific tasks. (b) The milestones pertaining to each task are denoted by M; I or II - indicate milestones aimed at before or after the midterm review. (c) First team listed in each task is the one responsible for it. (d) Obj. – denotes the pertinent project objective. (e) RM – denotes the pertinent research method. (f) The bar length indicates the schedule for the milestone (aimed to be achieved).

	Year 1	Year 2	Year 3	Year 4
WP1: Theoretical and Diagnostic Tools				
Task 1.1 **Dynamical QI flow to reservoirs/continua (Obj. A1, RM A) (Stockholm, Orsay, Vienna, Weizmann)**				
M1.1.1.II Space-time scales of QI flow, decoherence and quasiadiabaticity				
Task 1.2 **Internally-translationally entangled wavepackets (Obj. A2,D; RM A,D1)**				
M1.2.1 I QI flow, entanglement & decoherence **(Vienna, Weizmann, Orsay, Stockholm, Kaiserslautern)**				

	Year 1	Year 2	Year 3	Year 4
WP2: Interferometry and Probe Scattering				
Task 2.1 **Dimer interferometry (Kaiserslautern, Weizmann) (Obj. B1; RM B1,D1)**				
M2.1.1.I Molecular beam-splitter & mirror	■	■		
M2.1.2.I Feasibility of entanglement transfer from dissociated dimers to high-Q cavity fields or correlated beams	■	■	■	
M2.1.3.I Feasibility of molecular OPO-based interferometer	■	■	■	
M2.1.4.II Molecular interferometry		■		
M2.1.5.II Interferometric signatures of entanglement & decoherence		■	■	■
Task 2.2 **Macromolecular interferometry (Vienna, Kaiserslautern, Weizmann, Orsay) (Obj. A1,A2, B2; RM B2)**				
M2.2.1.I Slow-beam sources	■	■		
M2.2.2.I Beam-splitters & interferometers	■	■		
M2.2.3.II QI flow analysis	■	■	■	■
M2.2.4.II Lithographic gratings			■	■
Task 2.3 **Mesoscopic interferometry (Weizmann, Delft, Stockholm, Vienna) (Obj. B2,D1; RM B3,D1,D3,D4)**				
M2.3.1.I Construction of high-visibility interferometers	■	■		
M2.3.2.II Controlled-dephasing experiments and investigations of entanglement	■	■	■	■
Task 2.4 **Neutron scattering by correlated/entangled protons (Berlin/Uppsala/ISIS, Weizmann, Orsay, Vienna) (Obj. C; RM C)**				
M2.4.1.I Proton entanglement and decoherence in solids	■	■		
M2.4.2.II Entanglement of H and/or C atoms in organic materials		■	■	■
M2.4.3.II Feasibility of H entanglement effects in biological DNA			■	■

	Year 1	Year 2	Year 3	Year 4
WP3: Engineering/Control of Entanglement and Decoherence				
Task 3.1 **Theoretical development of entanglement control (Orsay, Kaiserslautern, Weizmann) (Obj. D1; RM D1,D2)**				
M3.1.2.I Entanglement control and transfer in complex (multi-level or multi-particle) systems	■	■		
M3.1.3.II QI processing in complex systems		■	■	■
Task 3.2 **Theoretical development of decay and decoherence control (Weizmann, Orsay, Delft) (Obj. D2; RM D1,D2)**				
M3.2.1.I Phase-amplitude modulation & non-holonomic control	■	■		
M3.2.2.II Control of decoherence and decay in multi-level systems	■	■	■	■
Task 3.3 **Exploration of entanglement and decoherence control in molecules and multi-atom/multi-proton systems (Orsay, Kaiserslautern, Weizmann, Vienna, Berlin) (Obj. B1,B2,D1,D2; RM B1,B2,D1,D2)**				
M3.3.1.I Feasibility of entanglement control in dimers via optical fields and field-induced (dipole-dipole) interactions	■	■		
M3.3.2.II Feasibility of entanglement control in Rydberg dimers		■	■	■
M3.3.3.II Feasibility of decoherence control in dimers and polyatomic molecules		■	■	■
Task 3.4 **Exploration of superconducting and/or semiconducting structures aimed at entanglement and decoherence control (Naples/Weizmann, Delft, Stockholm) (Obj. B2,D1,D2; RM B3,D3,D4)**				
M3.4.1.I Technologies for HTS junctions **(Naples)**	■			
M3.4.2.II Engineering of HTS circuits/mesoscopic structures **(Naples/Weizmann)**		■	■	■
M3.4.3.II Feasibility of entanglement and decoherence control in superconducting/mesoscopic structures **(Weizmann/Delft)**		■	■	■

• **Research Effort of the Participants**

Professional research effort on the network project			
Participant	Young researchers to be financed by the contract (person-months) (a)	Researchers to be financed from other sources (person-months) (b)	Researchers likely to contribute to the project (number of individuals) (c)
1. Weizmann/Delft	45	108	12
2. Vienna	44	96	10
3. Kaiserslautern	58	96	8
4. Orsay	33	96	7
5. Stockholm	22	48	4
6. Berlin/Uppsala/ISIS	35	48	6
7. Naples	46	64	7
Totals	283	556	54

Notes:
(a) TU **Delft**, the Netherlands, will act as subcontractor to the **Weizmann** node. Mutual visits of the senior staff and long secondments of young researchers (up to 10 months) will be used for joint research and training, as per tasks 2.3 and 3.4. Budget envisaged: Eur 10240 (in addition to the secondments).
(b) **Uppsala**, Sweden, and **ISIS** (Rutherford Appleton Lab.), UK, will act as subcontractors to the **Berlin** node. Extensive mutual visits will be used for joint work on Tasks 2.4 and 3.3. Budget envisaged: Eur 10000.
(c) During the course of the contract, a subcontract may be concluded between **Berlin** and **Lund**, Sweden, to perform work related to Task 3.3. Priority will be given to the network young researchers.

4 Organisation and Management

A. The coordinator will closely monitor (by e-mail, phone and semi-annual trips) the activities of each team.

B. The designation of a responsible team for each joint task (Sec. 3) will facilitate their coordination.

C1. The theory groups (at **Kaiserslautern, Orsay, Stockholm, Vienna** and **Weizmann**) will team up in the face of the challenging **WP1**. The demanding **tasks 1.1-1.2** will be jointly researched by these groups.

C2. Each experimental team will have one or more theoretical groups as *active partners* in the design of experiments and their analysis: i) **Task 2.2**: The **Vienna** group (with theoretical involvement of **Orsay** and **Weizmann**) will work with **Kaiserslautern**. ii) **Task 2.3**: The **Weizmann** (exp.) group (with theoretical involvement of **Weizmann/Delft and Stockholm**) will be assisted by the **Vienna** group; iii) **Task 2.4**: The **Berlin/Uppsala** will be assisted by the theoretical groups of **Weizmann, Orsay** and possibly **Vienna**. iv) **Tasks 3.2-3.3**: The close sharing of experimental design and techniques is envisaged by **Orsay, Kaiserslautern, Vienna** and **Berlin/Uppsala** (with theoretical involvement of **Weizmann/Delft** and **Orsay**). v) **Task 3.4**: The **Naples** group will be theoretically assisted by **Stockholm** and **Weizmann/Delft**.

D. The highest level of control over the research and training aspects of the network will be executed by a *Steering Committee*, consisting of the scientists-in-charge from all nodes and representatives of the young researchers, at the *annual* network conferences. Should the need arise, extraordinary meetings of the Steering Committee will be summoned. The network progress will be assessed by the Steering Committee based on the success of recruitment, mutual visits of participants and exchanges of young researchers between nodes, as well as the scope of collaboration and the number of joint publications.

E. The participation of *all* the young researchers at the annual network meetings will be strongly encouraged by the coordinator and the steering committee, as part of their responsibilities for the training of young researchers.

F. One of these annual meetings will include the midterm review, at which progress towards the milestones listed in Sec. 3 will be evaluated. If needed, these milestones and/or the schedule for their attainment will then be redefined.

G. Network progress reports and joint publications (e.g., in Phys. Rev., Phys. Rev. Lett., Europhys. Lett., Opt. Commun., J. Opt. B, Europhys. J.) will consolidate collaboration and ensure the effective dissemination of the results.

H. The publication of a *focus issue/review* of the network research in a European journal (e.g., J. Opt. B; Europhys. J.; Z. Naturforschung; Phys. Rep.) will be of high priority.

The chart below (Fig. 2) indicates the anticipated organization and interactions in the network.

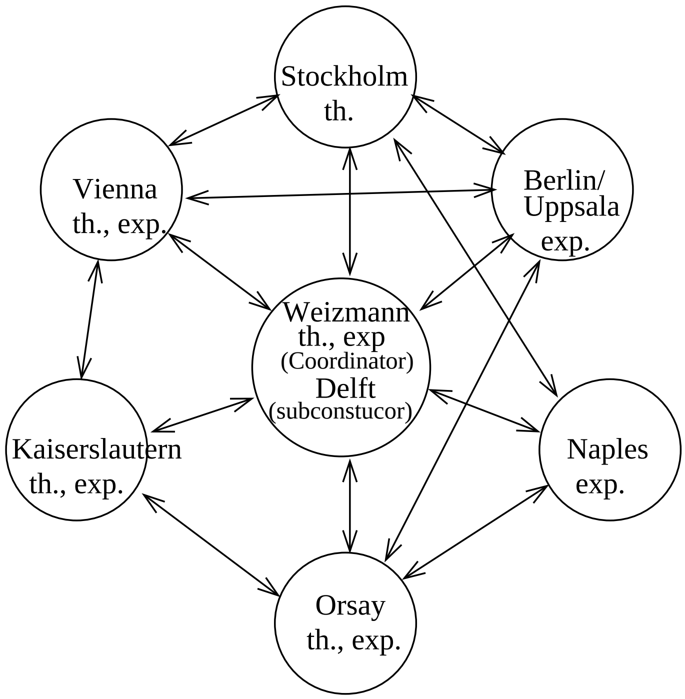

Figure 2: Organization and management structure.

5 Training

• Appointment of Young Researchers

A minimum overall total of 283 person-months will be provided by young researchers whose employment will be financed by the contract.

Young researchers to be financed by the contract				
Participant	Young pre-doctoral researchers to be financed by the contract (person-months) (a)	Young postdoctoral researchers to be financed by the contract (person-months) (b)	Total (a+b) (c)	Scientific specialities in which training will be provided (d)
1. Weizmann		45		P-03,-04,-07,-10,-13
2. Vienna		44		P-03,-04,-07,-14,C-08
3. Kaiserslautern		58		P-03,-04,-07
4. Orsay		33		P-03,-04,-07
5. Stockholm		22		P-03,-04,-07,-10,-13
6. Berlin		35		P-07,14,C-08
7. Naples		46		P-10,-13
Totals		283	**Overall Total** 283	

A. Recruitment will be facilitated by (i) the exchange policy within the network, as outlined in the Training Programme below; (ii) extensive advertising of available positions. The advertising will be undertaken, by the coordinator as well as by the other participants, via available electronic mailing lists, website advertisements and posters distributed among physics and chemistry departments and conference venues. Website advertising will be made, e.g., through TIPTOP, Association Bernard Gregory, JOST, WORKinOPTICS.com.

B. Typical lengths of appointments will range from 1 to 2 years, with the exception of Vienna, where a 44-month long appointment will be sought. Shorter appointments will be discouraged, unless they are in the framework of short-term exchanges between participants.

C. In case of recruitment difficulties experienced by any of the participants, a special effort will be made to direct there one or more young researchers from other nodes, as part of the rotation policy (see below). As last resort, redistribution of funds may be considered by the Steering Committee before the midterm point.

D. The recruitment of young female researchers will be strongly encouraged by the coordinator and the participants and discussed at network meetings. The creation of a congenial spirit for male and female young researchers alike will be continuously pursued by the coordinator and the participants, and will be raised at network meetings.

• Training Programme

1. The outstanding collective expertise, complementarity and multi-disciplinarity of the participant teams will be exploited to achieve *the following primary training objectives*:

a) train young theorists in a broad range of techniques pertinent to in-depth, quantitative analysis and control of entanglement and decoherence in complex systems;

b) train young theorists in close, active collaboration with experimentalists, aimed at helping them design new experiments and interpret their results;

c) train young experimentalists in designing, building and operating challenging novel setups, based upon deep understanding of the theory and the broad context of the issues;

d) help young researchers acquire experience in presenting their scientific results,under the close scrutiny of their peers.

2. *Complementary training objectives* will include:

a) the encouragement of tutoring and supervision of Ph.D students by postdoc trainees;

b) the involvement of postdoc trainees in networking and project management.

3. These objectives will be pursued through the following means:

a) Long-term, 6-12 month-long exchanges of young researchers will be strongly encouraged between all the groups, particularly for training on special instruments, such as ISIS (UK), the Braun Submicron Center (**Weizmann**) or the facilities at **Delft**.

b) Short-term exchanges of young researchers, 1-4 month-long, will be strongly encouraged in the framework of the *"rotation"* policy among *all groups.* This policy is meant to ensure that each young researcher is exposed to and participates in as many research tasks as possible within the various fields of the network.

c) Each visiting young researcher will be assigned a *mentor*, to provide both administrative and scientific guidance.

d)The annual network meeting will be held in the Young European Researcher format, with oral presentations by the young researchers. The scientists in charge will provide tutorials/overviews.

e) Winter or Summer Schools will be organized for theoretical and experimental training, with lectures given by well-known experts in pertinent fields. Discussion sessions, seminars and posters will be given and organized by the young researchers.

f) Each participant will be requested by the coordinator to send the young researchers to conferences, summer or winter schools and workshops. The resulting presentation titles will be included in the annual report and discussed at the annual network meetings.

4. *Multidisciplinarity* is *at the heart* of the QUACS network, encompassing (i) quantum dynamics, optics and information; (ii) molecule probing and manipulation by electromagnetic fields or neutron scattering; (iii) transport manipulation in superconductors and semiconductors. It will be inherent in both the individual training programme, due to the *collaborative components* of the experimental and theoretical tasks, as well as in the network-wide training. The long-term and short-term exchanges (the "rotation" policy explained above) will by necessity expose each young researcher to a *broad variety* of scientific disciplines. The multidisciplinary knowledge thus acquired will be systematized and consolidated during the annual network conferences.

5. *Connections to industry* may develop in the course of the network activity from the contacts that already exist between industry and several of the teams, should the network identify topics of promising R&D collaboration. Activities related to entanglement, decoherence control and matter-wave interferometry in molecules and solid structures have a potential for technological applications, hence the prospects for industrial collaboration. Should these prospects materialise, young researchers will be strongly encouraged to take part in both technical and commercial aspects of such collaboration.