European Science Foundation
Standing Committee for Physical and Engineering Sciences (PESC)

ESF PESC Exploratory Workshop on

Coherence, decoherence & entanglement of non-degenerate massive quantum systems

Vienna, Austria, 4 -7 October 2007

Scientific Report

Markus Arndt
University of Vienna

Executive summary

The workshop was convened by Markus Arndt (University of Vienna, Austria) and took place at the Erwin-Schrödinger Institute of Mathematical Physics (ESI) in Vienna, on October 4th to 7th.

The workshop was funded by the European Science Foundation (ESF-PESC), and generously supported by the Austrian Ministry of Science and Research (BM:WF), the Rectorate of the University of Vienna, the Faculty of Physics at the University of Vienna with additional 'contingent liability' through FWF projects held by Markus Arndt.

A dedicated web site has been set up with information about the meeting. This site is further accessible under "http://www.quantum.at/talksevents/esf-exploratory-workshop-coherence-decoherence-entanglement.html".

The workshop united physicists from very different sub-disciplines covering electron beam physics, neutron interferometry, atomic physics, photoelectron spectroscopy, mesoscopic solid state physics, macromolecule interferometry as well as particle physics.

The workshop had two major aims:

1. The exploration of fundamental questions related to coherence, decoherence, entanglement and genuinely complex quantum systems under many different theoretical and experimental angles.

2. The establishment of a platform which might enable new collaborations between groups which were only in loose contact or even completely uncoupled before.

All participants were provided with accommodation at Hotel Kaiser Franz-Josef, with easy access to the conference venue through a short tram connection. All meals during the workshop were organized by the convenor. Coffee breaks were provided at the Erwin Schrödinger Institute with help of our local assistants. Internet connection was made available through the ESI. Travel support was provided to all participants with predefined and reasonable upper limits - which in some cases were not even fully used, thanks to a very thoughtful and timely planning of most scientists.

The meeting was attended by 27 speakers from 11 different European countries as well as one speaker from the United States (Lincoln, Nebraska). The participants arrived on Thursday October 4th.
The meeting started on the morning of October 5th with an introduction by Dr. Farzam Ranjbaran, representing the European Science Foundation. The scientific lectures then discussed a multitude of interdisciplinary aspects related to coherence, decoherence and entanglement. The meeting ended formally on Sunday October 7th, but many informal discussions continued until the early evening of that day.
A formal time slot on Friday afternoon was dedicated to the inspiration of discussions about future collaborations. But – as already expected before the workshop – the majority of factual networking discussions emerged over lunch, dinner and the social event, i.e. in a relaxed atmosphere.

As detailed below, **all workshop goals were fully achieved**: The interdisciplinary science discussions were rated as very fruitful by the participants and the workshop was the trigger for a new ESF Research Networking Proposal that we initiated and submitted immediately after the completion of the ESF exploratory workshop.

Scientific content of the event:

The meeting brought together physicist focused on the physics of coherence, decoherence and entanglement in massive quantum systems. This comprises systems as different as electron beam physics, neutron interferometry, atomic physics, photoelectron spectroscopy, mesoscopic solid state physics, macromolecule interferometry as well as particle physics.

Electron interferometry belongs to the experiments that founded matter wave interferometry and modern quantum physics. Herman Batelaan (Lincoln, Nebraska) now discussed how to use it to further elucidate still open questions related to the Aharonov-Bohm effect. Originally coming from applied materials science, Johan Verbeck (Antwerp) showed the relevance of coherence and decoherence in electron microscopy.

Photoionization and photodissociation of diatomic molecules can even probe the coherence and decoherence of molecular core electrons of CO or N2 molecules or the spin entanglement in separated atoms. This was shown by Reinhard Dörner (Frankfurt) and Jarek Koperski (Krakow). These experiments derive their methods from physical chemistry and atomic physics.

Aris Dreismann (Berlin) presented his experiments and interpretations on neutron scattering anomalies in terms of coherence and decoherence.

Quantum experiments with atoms, neutrons and macromolecules were discussed by a large number of participants (e.g. Arndt, Leeuven, Nesvizhevsky, Peters, Rasel, Rauch, Vigué) with applications in precision metrology and matter wave lithography. These studies combine nuclear physics, atomic physics and molecular beam techniques and they promise new insights into many diverse fields, ranging from nanophysics to general relativity.

Coherence and entanglement was also an important topic with regard to atomic systems (Adams, Hackermüller, Polzik, Schmiedmayer). And also mesoscopic condensed matter systems (Gefen, Blaauboer) may act as host structures for electron interference and entanglement. This is interesting for quantum information applications but also important in itself as the decoherence phenomena in dense media are usually non-trivial.

Cooling, coherence and entanglement of cantilever based quantum systems (Aspelmeyer) was also identified as an interesting and growing research area in Europe.

The theory partners (Blaauboer, Gefen, Hiesmayr, Hornberger, Morigi, Opatrny, Son, Wang) put forward a great number of interesting proposals, shedding new light on the complementarity principle, the use of entanglement witnesses in macroscopic quantum systems, cavity quantum electrodynamics, electrons in mesoscopic system, entanglement in the Kaon system, macromolecule interferometry and the potential role of gravity in quantum decoherence.

Assessment of the results:

The meeting was generally regarded as an excellent opportunity for bringing together scientists with related interests but originating from different sub-disciplines of physics.

It is the very nature and objective of ESF exploratory workshops to identify possible fields of collaboration and to trigger joint projects on the European level.

The workshop was highly successful in this regard, since several partners started scientific collaborations on a very practical level.

The present report, of course, cannot reflect all private discussions and agreements but it became clear that a significant number of scientific and informal collaboration discussions were triggered by the ESF exploratory workshop. The following examples are limited to the experience of the convenor himself:

Herman Batelaan and Markus Arndt got together to discuss the secondment of students to a third ESF partner in Germany (F. Hasselbach). Gershon Kurizki (Israel) is involved in collaboration discussions with Jörg Schmiedmayer (Austria) and the visit in October was the trigger for another meeting (Schmiedmayer, Kurizki, Arndt) in November. The groups in Krakow (Koperski) and Vienna (Arndt) now aim at intensifying the already existing student exchange program between both institutions and arranged a follow-up visit for spring 2008. Similarly the already existing good scientific relations between the partners in Vienna, Munich and Mainz were intensified: a joint publication was discussed and a former diploma student from Munich is working as a PhD student in Vienna since December 2007. All matter wave groups shared valuable information on experimental details and several theoretical ideas were shared for the first time between the theorists and the experimentalists.

Even more importantly, during lunch breaks and dinner meetings, it was agreed by a large number of participants, that it would be valuable to prepare the submission of an application for a follow-up research networking proposal under the roof of the European Science Foundation. This was a somewhat bold idea, since the deadline for the last open call was very close.

A proposal was then drafted by Markus Arndt (Vienna), Yuval Gefen (Rehovot), and Giovanna Morigi (Barcelona) with input and agreement by a large number of participants of the ESF exploratory workshop. The composition of the consortium and the rather interdisciplinary scientific scope of this proposal were able to attract further high-level scientists from the ENS in Paris, the TU Delft, the ETH Zürich, the University of Basel and other European top research institutions.

The group of proposers submitted the **new project "*Coherence, Decoherence and Entanglement in MAssive Quantum Systems*" (CODEMAQS),** as an **ESF Research Networking Programme** by October 31st 2007**.** This project is aiming at strengthening the European quantum community through workshops, secondments, collaboration visits and

international conferences. The accomplished ESF exploratory workshop in Vienna – with a total budget of about 20.000 € - was thus able to trigger a follow-up science networking proposal with an even larger group of European top scientists, with a financial volume of about 600.000 €. The new project is currently under scientific review at the European Science Foundation.

Final programme

Fri. Oct. 5th			
8:40-9:00	F.	Ranjbaran	Presentation of the European Science Foundation (ESF)
9:00-9:35	E.	Polzik	Engineering entangled states of large atomic ensembles with light
9:35-10:10	H.	Rauch	Depolarisation, dephasing and decoherencing in neutron optics
10:10-10:45	Ch.	Adams	Coherence, decoherence, and entanglement using Rydberg dark states
10:45-11:15	**Coffee Break**		
11:15-11:50	W.	Son	Entanglement Production in Non-Equilibrium Thermodynamics
11:50-12:25	M.	Aspelmeyer	Quantum Optomechanics – from laser-cooling to entanglement in micromechanical systems
12:25-13:00	Y.	Gefen	Weak values of electron spin in a double quantum dot
13:00-14:30	**Lunch Break**		
14:30-15:05	M.	Blaauboer	Quantum random walk of electrons in a solid-state nanostructure
15:05-15:40	A.	Dreismann	Attosecond physics and chemistry with neutron and electron Compton scattering: New aspects of chemical bond dynamics
15:40-16:10	**Coffee Break**		
16:10-16:45	R.	Dörner	Coherence, decoherence and entanglement in molecular photoionization
16:45-17:20	T.	Opatrny	Path-phase duality of an interfering particle with translational-internal entanglemen
17:20-18:30	**Discussion of possible follow-up research activities & collaborative actions**		
	Informal Dinner		

Sat. Oct. 6th			
9:00-9:35	H.	Batelaan	Phase versus force
9:35-10:10	B.	Hiesmayr	What has a symmetry violation in high energy physics to do with nonlocality and entanglement?
10:10-10:45	J.	Koperski	Test of the Bell inequality for atoms - experiment with mercury dimers
10:45-11:15	**Coffee Break**		
11:15-11:50	A.	Peters	Atom interferometry – current sensitivity limitations and concepts for future improvements
11:50-12:25	G.	Kurizki	Detection anomalies in space and time
12:25-13:00	K.A.H.	van Leeuwen	Quasi-Bragg scattering of atoms: magnetically tunable beam splitters for interferometry
13:00-14:30	**Lunch Break**		
14:30-15:05	G.	Morigi	Quantum Reservoir Engineering of the Electromagnetic Field
15:05-15:40	J.	Verbeeck	Transmission electron microscopes as quantum optical bench for coherency experiments
15:40-16:15	L.	Hackermüller	Ultracold quantum gases in optical lattices
16:15-16:45	**Coffee Break**		
16:45-17:25	V.	Akulin	Entanglement Description with Nilpotent Variables & the Application for Control of Atomic Entanglement in Optical Cavities
17:25-18:00	E.M.	Rasel	Prospects of Matter Wave Interferometry
18:00-18:35	K.	Hornberger	Emission-time entanglement of massive particles
	Social event "Heuriger"		

Sun. Oct. 7th			
9:00-9:35	V.	Nesvizhevsky	Gravitationally bound quantum states of neutrons. Coherence, decoherence, entanglement
9:35-10:10	Ch.	Wang	Quantum Gravitational Decoherence of Massive Objects
10:10-10:45	J.	Vigué	Atom interferometry with lithium atoms at thermal energy
10:45-11:15	**Coffee Break**		
11:15-11:50	J.	Schmiedmayer	Entangling Atoms by Interfering Photons
11:50-12:25	H.	Ulbricht	Applications of molecule interferometry
12:30-14:30	**Lunch Break**		
	Time for informal discussions		

Statistical information on the participants

Number of scientific speakers	**27**
Number of official participants	**29**
Number of guests	**2**
Number of Countries	**12**
Austria	**6**
Belgium	**1**
Czech Republic	**1**
Germany	**6**
Denmark	**1**
Spain	**1**
France	**3**
Italy	**1**
Netherlands	**2**
United Kingdom	**3**
USA	**1**
male	**23**
female	**5**
Theory	**10**
Experiment	**18**
not older than 40	**11**

The participants also included:

- The ESF representative, Dr. Farzam Ranjbaran
- Markus Arndt as the scientific organizer and convenor of the meeting.

… as well as intermittently:

- Anton Zeilinger in his role both as a top-scientist and as one of the co-sponsors of this meeting (as the Dean of the Faculty of Physics at the University of Vienna).
- Mrs. Natacha Voillot-Blumenthal, a documentary filmer, who came on her own account. She was admitted to the sessions and meals after agreement by the ESF.

Final list of participants

Name		Department/Faculty	Institution	Street / No.	City	P.O.	Country
Charles	Adams	Department of Physics	University of Durham	South Road	Durham	DH1 3LE	UK
Vladimir	Akulin	Laboratoire Aimé Cotton	Orsay	Bat 505, Campus d'Orsay	Orsay	91405	F
Markus	Arndt	Quantennanophysik	University of Vienna	Boltzmanngasse 5	Vienna	1090	A
Markus	Aspelmeyer	IQOQI	Austrian Academy of Sciences	Boltzmanngasse 3	Vienna	1090	A
Herman	Batelaan	Physics and Astronomy	University of Nebraska, Lincoln	116 Brace Lab	Lincoln	68588-0111	USA
Miriam	Blaauboer	Kavli Institute of NanoScience	TU Delft	Lorentzweg 1	Delft	2628 CJ	NL
Reinhard	Dörner	Institut für Kernphysik	Universität Frankfurt	Max-von-Laue-Str.1	Frankfurt a. M.	60438	D
Aris	Dreismann	Institut für Chemie	TU Berlin	Straße des 17. Juni 115	Berlin	10623	D
Yuval	Gefen	Condensed matter Physics	Weizmann Institute	PO Box 26	Rehovot	76100	IL
Lucia	Hackermüller	Institut für Physik	University of Mainz	Staudingerweg 7	Mainz	55128	D
Beatrix	Hiesmayr	Fakultät f. Physik	University of Vienna	Boltzmanngasse 5	Vienna	1090	A
Klaus	Hornberger	Arnold Sommerfeld Zentrum	LMU, Munich	Theresienstr. 37	Munich	80333	D
Jaroslaw	Koperski	Smoluchowski Institute of Physics	Jagiellonian University	ul. Reymonta 4	Krakow	30-059	PL
Gershon	Kurizki	Department of Chemical Physics	Weizmann Institute	PO Box 26	Rehovot	76100	IL
Giovanna	Morigi	Optics group	University of Barcelona	Bellaterra	Barcelona	*08193	ES
Valery	Nesvizhevsky	Institute Laue-Langevin	ILL Grenoble	6 rue Jules Horowitz	Grenoble	38042	F
Tomas	Opatrny	Department of Theoretical Physics	University Olomouc	Třída 17. listopadu 50	Olomouc	77200	CZ
Achim	Peters	AG Quantenoptik und Metrologie	Humboldt-Universitaet zu Berlin	Hausvogteiplatz 5-7	Berlin	10117	D
Eugene	Polzik	Nils Bohr Institute	University of Copenhagen	Blegdamsvej 17	Copenhagen	2100	DK
Ernst Maria	Rasel	Institut für Quantenoptik	Universität Hannover	Welfengarten 1	Hannover	30167	D
Helmut	Rauch	Atominstitut	TU Vienna	Stadionallee 2	Vienna	1020	A
Jörg	Schmiedmayer	Atominstitut	TU Vienna	Stadionallee 2	Vienna	1020	A
Wonmin	Son	School of Physics and Astronomy	University of Leeds	The University of Leeds Campus	Leeds	LS2 9JT	UK
Hendrik	Ulbricht	Quantennanophysik	University of Vienna	Boltzmanngasse 5	Vienna	1090	A
Ton	van Leeuwen	Applied Physics	TU Eindhoven	PO Box 513, NLg 2.08 / NLa 1.20	Eindhoven	5600 MB	NL
Johan	Verbeek	EMAT	University of Antwerp	Groenenborgerlaan 171	Antwerp	2020	B
Jacques	Vigué	Laboratoire CAR	Université Paul Sabatier	118, route de Narbonne	Toulouse	31062	F
Charles	Wang	Mathematical Sciences	University of Aberdeen	S002 Fraser Noble Building	Aberdeen	AB24 3UE	UK