The QUEST of Science
Music or Physics?

Max Planck asked the expert:

“Physics, that is a fairly nice subject, but you will not be able to find anything fundamentally new in it. In this science, almost everything has been discovered already and only a few unimportant gaps remain to be filled!”

Phillip Gustav Jolly (Professor of Physics in Munich) to Max Planck in 1874
Unimportant Gaps?
Einstein‘s Annum Mirabilis 1905

Annalen der Physik, Band 17, Seite 132-148
6. Über einen
die Erzeugung und Verwandlung des Lichtes
betreffenden heuristischen Gesichtspunkt;
von A. Einstein.

Annalen der Physik, Band 17, Seite 549-560
5. Über die von der molekularkinetischen Theorie
der Wärme geforderte Bewegung von in ruhenden
Flüssigkeiten suspendierten Teilchen;
von A. Einstein.

Annalen der Physik, Band 17, Seite 891-921
3. Zur Elektrodynamik bewegter Körper;
von A. Einstein.

Annalen der Physik, Band 18, Seite 639-641
13. Ist die Trägheit eines Körpers von seinem
Energieinhalt abhängig?
von A. Einstein.

- Photoeffect, Quantum Mechanics
- Brownian Motion
- Special Relativity
- Equivalence Principle
Yesterday’s Gaps are Today’s Tools
But: The Common Picture is Still Missing
Cluster of Excellence
QUEST
Research at the quantum limit!
Overview

• Motivation
• Introduction of QUEST
• Mission and Structure
• Insight in QUEST’s Research
• Some Results *exemplified*
Acronym **QUEST**: Centre for **Quantum** Engineering and **Space-Time** Research

Quantum-Engineering + Space-Time-Research = \(\text{quest}\)
Todays Gaps:

- Gravitation
- Strong Interaction
- Elektromagnetic
- Weak Interaction
QUESTs of Today

• Link between die quantum mechanics and gravitation?
• How did “Big Bang” work?
• What is Dark Matter and Energy?
• What happens inside a Black Hole?
• What is behind quantum physics?
• Can we master Quantum Computing?
• Properties of Gravitational Waves?

More questions anyone can answer immediately!
Research Quests in QUEST

• Understanding the quantum world
  – Nanoscopic quantum world
  – Mesoscopic quantum world
  – Macroscopic quantum to classical world

• Quantum – Gravity?
  – Equivalence principle
  – Constancy of physical constants

• Structure of the universe
  – Preferred frame research
  – Gravitational wave astronomy
Research Routes in QUEST

• Strongly correlated systems
  – Macroscopic entanglement

• Matter wave interferometry
  – Atom lasers, gravitational sensors

• Atomic clocks
  – On earth and in space

• Light interferometry beyond all limits
  – Quantum non-demolition and squeezing

• Laser ranging
  – Relativity, geodesy and gravity gradiometry
Engineering at Quantum Level

Engineering with ...

![Photons](image1)

![Atoms](image2)

![Elektrons](image3)

Results ...

![New States of Light](image4)

![Atom Lasers](image5)

![Quantum Information](image6)
Space-Time-Research?

Cosmology and Quantum-Gravitation

Precision Geodesy

Gravitational Waves
How does QUEST work?

Quantum-Sensors

Enabling Technologies

Quantum-Engineering

Space-Time Research
Who is QUEST?

Institutes of Leibniz Universität Hannover

External Partners

26/11/2008 W. Ertmer
Institutes of Leibniz Universität

Theoretical Physics

Stringtheory
Gravitation
Quantum Optics

Solid State Physics

Gravitational-physics
Quantum Optics

Theoretical Physics
External Partners

Centre for Applied Space Technologies and Microgravity (ZARM)

Technology
Space-Time Research

International Networking
Excellent Theory
## Task Groups in QUEST (Matrix)

- Task Groups as flexible research units
- Task Groups address multi-area challenges
- Task Groups are “work benches” for new visions

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TG 2: Cold Atom Test of the Principle of Equivalence (Caprice)

- All-optical fountain for ultra cold matter
- Testing the equivalence principle by using $^{40,41}$K $^{85,87}$Rb

www.finaqs.uni-hannover.de
- **Problem:**
  Frequency stability of the best lasers is limited by thermal noise in the optical resonator
- **Solution:**
  We use a 1.5 μm stabilised to a silicon single crystal resonator (large Q) at 100 K and a fibre comb
Transportable strontium clock laser

**Deliverable:**
- Transportable 698 nm laser system
- Linewidth < 1 Hz, total volume < 1000 l.

**Volume:** 330 l

**Laser system completed:**
- Available for experiment and frequency measurement
- High reliability (> 1 week in lock)

**Master**
- $P_{opt} = 4$ mW

**Slave**
- $P_{opt} = 23$ mW
Quantum technology

• Demonstration of a high-reflectivity waveguide mirror (a single dielectric coating layer plus a nanostructured surface provides >99% reflectivity)

[[Brückner et al., Opt. Lett., submitted]]

• Proposal für a new light/matter interface: a monolithic high-reflection mirror without any dielectric coating.

Waveguide Coatings

100% reflectivity

99% reflectivity realized:

Monolithic 100% reflection “coating”
TG 6: QND Detector for a Gravitational Wave Detector

10m prototype interferometer

Infrastructure in prototype hall, including pumps, pump lines, and valves, AC/DC power distribution, network access, seven optical benches, steel work, paint and brick layer work is (almost) completely in place.

Ultra-high vacuum system (Volume ca. 100 m³, 22 t stainless steel) will be delivered and fully installed in December.

FEA analysis based design of in vacuum suspended optical benches nearing completion.

Monolithic accelerometers chosen as inertial reference sensors; collaboration with VIRGO labs established.
For example:

SOME RESULTS
Claus Lämmerzahl, ZARM

Group
„Quantum Gravity Phenomenology“
Quantum gravity phenomenology

- Space-time fluctuations: metrical fluctuations minimally coupled to quantum equations

  - Induce apparent violation of the equivalence principle, testable with atomic interferometry
    (E. Göklü & C. Lämmerzahl, *Class. Quantum Grav.* 25, 105012 (2008))

  - Induce apparent decoherence in atomic systems, but long decoherence time for single particle states
    (H.-P. Breuer, E. Göklü & C. Lämmerzahl, submitted)
Uwe Morgner, LUH (IQ)

Group
„Advanced Optical Field Synthesis”
(atto-second-physics)
Few-Cycle Femtosecond Field Synthesizer

• Full control over the electric field of few-cycle laser pulses by:
  – Spectral phase and amplitude
  – Carrier envelope offset phase

• Arbitrary spectral and temporal pulse conditioning:
  – Generation of 3.6-fs-laser pulses
  – Field shaping with sub-femtosecond resolution
  – Blanking of wavelength regions, edge-filtering
  – Towards as-frequency combs

Jürgen Müller, LUH (ife)

Group

„Precision Geodesy on Earth and in Space“
Research Activities in Geodesy

- Evaluation of satellite data, preparation of new gravity field satellite missions
- Relativity tests (gravitational constant, equivalence principle, metric) from 38 years of LLR data
- Earth system research

• Analysis of clock errors in GNSS
Relativistic Parameters from LLR

- Gravito-magnetic effect in equations of motion via preferred-frame parameter (here, coupled with dynamics within the solar system),

\[ \alpha_1 \leq \pm 4 \cdot 10^{-3} \]

(Soffel et al., 2008, Phys.Rev.D, 78)

- Strong Equivalence Principle, new limit for Nordtvedt parameter

\[ \eta \leq \pm 7 \cdot 10^{-4} \]

(Müller and Biskupek, 2007, Class.Quant.Grav., 24)

- Secular and quadratic variation of the gravitational constant

\[
G = G_0 \left(1 + \frac{\dot{G}}{G} \Delta t + \frac{1}{2} \frac{\ddot{G}}{G} \Delta t^2 \right)
\]

\[
\frac{\dot{G}}{G} \leq \pm 7 \cdot 10^{-13} \text{ yr}^{-1}
\]

\[
\frac{\ddot{G}}{G} \leq \pm 5 \cdot 10^{-15} \text{ yr}^{-2}
\]

All results confirm Einstein’ s theory impressively.
Work in Hannover on gravity field missions

• Aim: follow-on mission for GRACE
• No specific mission plan at this moment
• But: enormous interest worldwide
• Our aim: investigate and develop central components
• final product: A consistent and complete mission design including data analysis
working approach

Classical top down design

Mission science requirements

IFE

Data processing

IFAM

Earth modelling

IFE

Configuration and orbits

Orbits

Drag-Free
Yes/No?

Interspacecraft links (laser ?)

Local measurements: acceleration/rotation?

Number of Spacecraft?

Payload performance requirements

Thrusters

Interferometer

Accelerometer/Gyroscope

Attitude control

Timing, clocks, Orbit determination

IQ, ZARM

We begin at many and simultaneous
Interferometer technology overlap
LISA ↔ future geodesy missions

- Heterodyne laser interferometry on long distances with telescopes
- Same frequency range (mHz)
- Stable optical benches
- Offset phase locking of lasers
- Phase measurement system
- Absolute ranging and clock synchronization
- Optical sensing of a free floating test mass
- Data transfer on the optical link
- Alignment tracking and autonomous acquisition
Large overlap in technologies

Ample performance margin
Roman Schnabel, LUH (IGP), Karsten Danzmann, LUH(IGP), AEI

Group “Non-Classical Interferometry”
Generation of Squeezed Light

$\chi_2$-nonlinear crystal: MgO:LiNbO$_3$

Standing wave cavity

Crystal housing / Squeezed light source based on optical parametric amplification (OPA)
Generation and Observation of Squeezed Light

99.8% visibility
Squeezed Light Generation (OPA)
Observation of 10 dB Squeezing

- Vacuum noise (shot-noise) (a)
- Squeezed noise (b)
- Detector dark noise (c)

10.1 dB, factor of 10 noise power reduction

[Vahlbruch et al., PRL 100, 033602 (2008)]
(9dB: [Furusawa et al., Opt. Exp. (2007)])

[42] [Vahlbruch et al., PRL 100, 033602 (2008)]
Observation of 10 dB Squeezing

Intrinsic loss (7.1 ± 1.5) %

- (a) Vacuum noise
- (b) Squeezed vacuum noise
- (c) Antisqueezed vacuum noise
New developments

• Observation of >5dB squeezing at 1550nm, which might be the wavelength of future GW detectors with silicon mirrors

[Mehmet et al., in preparation for Optics Letters (2008)]
Squeezing at 1550nm

Noise powers of anti-squeezing, vacuum noise and squeezed noise, as well as for a scanned quadrature angle.
Latest Results

• First observations of 11dB squeezing and strong photon number oscillations.

[Mehmet et al., in preparation for Nat. Photonics (2008)]
Squeezing in the Photon Picture

Measured photon number probability distribution

- Vacuum
- 3dB sqz
- 6db sqz.
- 11db sqz.
Applications

• Observation of squeezing at audio-band Fourier frequencies

[Vahlbruch et al., New J. Phys. 9, 371 (2007)]

Photographs show protection against scattered and frequency shifted photons
Squeezed light source for GEO600
Squeezed Light in the Audio-Band

(d) Vacuum noise level, $P_{LO} = 464 \, \mu W$
(e) Squeezed noise, $P_{LO} = 464 \, \mu W$
(f) Electronic dark noise


First audio-band squeezing:
Macroscopic Entanglement

• Proposal for the generation of entangled mirrors (entanglement of positions and momenta of centre of masses of two suspended mirrors)

[Müller-Ebhardt, Rehbein, Schnabel, Danzmann, and Chen, PRL 100, 013601 (2008)]

Semi-popular articles:
[Schnabel, Spektrum der Wissenschaft (2008)]
[Schnabel, Müller-Ebhardt, Rehbein, Physik in Unserer Zeit 39, 234 (2008)]
Light / Mirror Quantum Systems

Radiation pressure coupling of light and mirror

GEO600
Entangled Mirrors

A. Franzen, AEI

[Müller-Ebhardt, Rehbein, Schnabel, Danzmann, and Chen, PRL 100, 013601 (2008)]
Entangling Test Masses

Additional detection of bright port can provide quantum regime for also the common mode.

[Müller-Ebhardt, Rehbein, Schnabel, Danzmann, Chen, PRL 100, 013601 (2008)]
Entangled Mirrors

Radiation pressure entangles mirror motion and the light’s quadratures

Interference at beam splitter realizes entanglement swapping

Problem of back-action noise and thermal noise can be solved through conditional states
Jan Arlt, Carsten Klempt, W.E., LUH (IQ)

Group “Quantum Engineering with Ultra Cold Gases”
Association of heteronuclear molecules

Radio frequency association of heteronuclear Feshbach molecules
Accepted in Phys. Rev. A (R)
Damping in disordered systems

Damped Bloch Oscillations of Bose-Einstein Condensates in disordered Potential Gradients


Ernst Rasel, W.E., LUH (IQ)

Group “Atomic Quantum Sensors”
Cooling Metastable Magnesium

Singlet

$^1S_0 \rightarrow ^1P_1$

285 nm 80 MHz

Triplet

$^3D_j \rightarrow ^3P_j$

285 nm 80 MHz

383 nm

$t$-MOT

$s$-MOT

$10^8$ atoms, 3 mK

$polarisation$ gradient cooling possible $\rightarrow \mu K$

Next steps:

- Optical molasses cooling, dipole trap
- Investigations of collisions

$s$-MOT: $^1S_0 \rightarrow ^1P_1$ $10^9$ atoms, 3 mK

$t$-MOT: $^3P_2 \rightarrow ^3D_3$ $2 \times 10^8$ atoms, 1 mK
Frequency comparison Hannover-Braunschweig via telecom fiber network

- Servo bandwidth of approx. 200 Hz limited by length of fiber link
- Stabilized fiber link shows Allan standard deviation of transferred light of
  \[ \sigma_\gamma(\tau) = 2.5 \times 10^{-15} \tau^{-1} \]
  H. Schnatz, G. Grosche, PTB

Summery

• Establishment of QUEST as new Research Centre on a very promising track
  – In total 9 new Professorships
    • most positions filled beginning 2009
  – 17 Post-Docs and Junior-Professorships
  – 31 PhD-Positions

• New developments in quantum engineering, space-time research and its applications for fundamental and applied research
Thank you very much for attention