Quantum Devices & Systems
Congressino gruppo 5
03-02-2021
G. Rosi
Sommario

• Esperimenti «quantum» già presenti in sezione:
  – OLAGS
  – NaMaSSTE

• «Idee» provenienti da attività Gruppo 2
  – Humor (tHEEOM-RD)
  – Supremo
OLAGS COLLABORATION

Genova (1 FTE, coordination)
Firenze (1 FTE)
Pisa (2.5 FTE)
LNF (0.4 FTE)
Atomic gravimeters

- They are based on atomic interferometry: laser cooling + coherent manipulation of atomic wave packets
- They are the best absolute gravimeters: sensitivity of the order of 10 µgal / √Hz demonstrated, accuracy ~ 1 µgal (1 µgal = 10^{-8} m / s^2)
- Seismic noise is one of the main sensitivity limits
Atomic gravity gradiometer

- Two vertically separated atomic samples
- Interrogation with the same laser field for the manipulation of the atomic wave packet
- Demonstrated a CMRR better than 140 dB for seismic noise
- Demonstrated differential sensitivity of $5 \cdot 10^{-11} \text{g}$ @10000 s with baseline of 30 cm
Gradiometer Scalability

- With $n+1$ equally spaced atomic samples the $n$th spatial derivative of the gravitational field is measured.
- Demonstrated e.g. for measuring the curvature of the gravitational field (G. Rosi et al., PRL 114, 013001 (2015))
Gradiometer Scalability

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- Demonstrated eg. for measuring the curvature of the gravitational field (G. Rosi et al., PRL 114, 013001 (2015))
- The sensitivity in the gradient measurement depends on the distance between the sensors Ultra-sensitive measurements require large equipment
  - Large fountains \( \sim 10 \) m (Stanford, Hannover)
  - Horizontal optical cavity \( \sim 300 \) m, (LNBB, Francia, progetto MIGA)
  - Proposals for laser links between distant satellites: AGIS, AGIS-LEO, SAGE
OLAGS: base concept

- Demonstrate the possibility of measuring the gravitational gradient with two distant atomic sensors
- Use the same laser field to interrogate the two gravimeters, using a coherent optical link
  - Fiber optical link
    - Optical metrology methods for fiber-induced phase noise cancellation via two-way link
OLAGS: base concept

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Application areas

• Earth and environmental physics
  – Solid earth physics
  – Fluid Earth Physics

• Detection of gravitational waves
  – Low frequency Newtonian noise measurement for 3rd generation detectors
  – Stochastic background measurement using normal earth modes

• Fundamental physics
  – Research of Dark Matter
## Participants - Pavia, Firenze and Milano Units

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<tr>
<th>Participant</th>
<th>Unit</th>
<th>FTE/year</th>
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<tr>
<td>Manuel Mariani – RU – UNIPV – PI</td>
<td>Pavia</td>
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<td>Davide Cicolari – PhD – UNIPV</td>
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<td>Marta Filibian – Technician - UNIPV</td>
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<td>Elio Giroletti – Senior Member – INFN</td>
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<td>Alessandro Lascialfari – PO – UNIPV</td>
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<td>Lisa Rinaldi – PhD – UNIPV</td>
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<td>Fabio Cinti – RTDB – UNIFI</td>
<td>Firenze</td>
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<td>Maria Fittipaldi – RU – UNIFI</td>
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<td>Giuseppe Latino – PA – UNIFI</td>
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<td>Lorenzo Sorace – PA – UNIFI</td>
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<tr>
<td>Francesco Orsini – Technician – UNIMI</td>
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### External Participant:

P. Santini – PO, Department of Mathematical, Physical and Computer Sciences, University of Parma
NAMASSTE project aims to design, synthesize, and characterize new molecular nanomagnets (MNMs) for two different applications:

- high-density memory storage systems
- high-sensitivity sensors potentially suited for revealing dark matter

MNMs are crystalline materials composed by identical magnetically isolated molecules showing slow relaxation of the magnetization of pure molecular origin, and thus magnetic bistability, below a given temperature.

These aims will be pursued by combined experimental and theoretical approach involving the synergic work of Physicists and Chemists.

- World data generation: 25 Pbytes / day
- Generation is increasing faster than data storage capability
**Molecular Nanomagnets (MNMs)** (systems size of the order of nanometers):

- regular crystalline structure with a magnetic core of a finite number \((n \geq 1)\) paramagnetic centers (strong intramolecular exchange interactions)
- molecules shielded by organic ligands → weak intermolecular interactions

**SMMs:** 3d Single - Molecule Magnets \((\text{Mn}_{12}, \text{Fe}_4)\)

**SIMs:** 4f Single - Ion Magnets \((\text{Ln} – \text{Zn} \text{ and } \text{Ln} – \text{tropolonato systems})\)
$D \approx 0.7 \text{ K}$

$S_{\text{tot}} = 10$

$\tau_0 \approx 10^{-7} \text{s}$

$\Delta E/k_B \approx 65 \text{ K}$

NAMASSTE – SMM state of art

Sessoli et al. Nature 1993
Christou et al. MRS Bull. 2000
Molecular spins in MNMs represent a possible interesting alternative, with respect to other spins systems currently investigated (NV centers in diamonds).

Their potentialities as quantum probes for external electric and magnetic fields are still largely unexplored.
NAMASSTE: Methods

Theoretical and experimental investigations of the spin dynamics of SIMs to find relationships between chemo-physical properties and the magnetic properties to conceive new design principles for improving their working temperatures as magnetic molecular memories.

Experimental studies to identify the best SMM with the highest sensitivity as particle sensors.
Experiments of MNMs as Sensors

For the first time, recent experiments validated SMMs as quantum sensors

We will compare, through NMR, ESR, and SQUID Magnetometry as a function of the magnetic field, the experimental results obtained on SMMs in normal conditions and in presence of a low-activity radioactive source, in order to:

a. increase the overall detection sensitivity thank to the use of more sensitive techniques than that used by Chen et al.*

b. increase the temperature of use of SMMs as sensors (higher energy barriers and $T_B$)

tHEEOM-RD

technology for High Efficiency Electro Optical Modulator

Responsabile nazionale: Enrico Serra  TIFPA

Unità partecipanti: Trento, Perugia (+Firenze)

- Francesco Marin – Professore Associato – Università di Firenze - FTE 0.2
- Francesco Marino – Ricercatore CNR-INO – FTE 0.3

Spin-off della tecnologia sviluppata per HUMOR
Development of Electro-Optical-Modulators (EOM) for transduction of the weak RF signals

\[ H = \sum_{i=1}^{2} \left[ \frac{p_i^2}{2m_i} + \frac{m_i\omega_i^2 x_i^2}{2} \right] + \frac{\phi^2}{2L} + \frac{q^2}{2C(\{x_i\})} - qV. \]

Membrane + ed electrode

Electro - mechanical coupling constant

\[ G_i \approx -\frac{V_{dc}}{C_0} \frac{\partial C_m(\{x_i\})}{\partial x_i} \bigg|_{x_i = \bar{x}_i} \]
Circular-shaped resonator developed for HUMOR

Resonator base on high-stressed 1 GPa 100 nm - Si₃N₄ membrane – D=1.560 mm

- High-Q factor > 10⁷ over a [1-5] MHz bandwidth and good separation between mode

Requirements for tHEEOM-RD:
- Geometrical optimization of the electrodes exploiting circular symmetry
- Controlling possible increase of dissipation due to the metal layer
- Bonding strategy for reducing electrode gap to 3-8 um
Optimizing the electro-mechanical coupling

Fundamental requirements:
1) minimizing the gap $h_0$ (3 - 8 um)
2) maximizing $A_{eff}$
3) plane alignment (< 50 um accuracy)
4) best parallelism between the electrodes (< 1 mrad)
Technology for integrating the TiN electrode (2019-2020)

Electrode integration: sputtering of 25 nm TiN film @ 350 °C

TiN is CMOS compatible & cryogenically compatible

After HF wet etching release and cleaning
Technology development for the fixed electrode (2020)

Microfabricated fixed electrode has the required planarity for minimizing optical losses.

- **KOH wet-etching/ DRIE recession H** to reach a 3-8 um gap
- Patterning metal lines over a thick SiO₂ (3 um) thermal oxide. Very good insulation from the silicon substrate is needed.

Chip-to-chip bonding + Cavity assembly (2021)

TEM SiNx nanoreactor assembly  Optomechanical SiN two membrane sandwich

**EXAMPLES of assembly**
**SUPREMO:**

using molecular spectroscopy to measure variations of $\beta$.

\[
\frac{1}{\nu(S)} \frac{\partial}{\partial t} \left[ \frac{\nu(S)}{\nu(Cs)} \right] \simeq -\frac{1}{2\beta} \frac{\partial \beta}{\partial t}
\]

Frequency of a given molecular ro-vibrational transition relative to the clock hyperfine transition in the Cs atomic clock

_Florence Group Members:_
Simone Borri (INO-CNR)
Giacomo Insero (INO-CNR)
Gabriele Santambrogio (INRIM)

_Napoles Group Members:_
Pasquale Maddaloni (INO-CNR)
Valentina Di Sarno (INO-CNR)
Roberto Aiello (INO-CNR)
The electric dipole moment (EDM) of fundamental particles

Parity violation

• Variations of fundamental constants
• Test of QED and search for a fifth force
• Determination of the Boltzmann constant
Instrument: a mid infrared laser referenced to the primary frequency for molecular spectroscopy

Usage: CO ro-vibrational transition measured with **11-digit accuracy on a molecular beam**
Temperature of the molecules is the current limit.

→ Colder molecules by buffer gas cooling + laser cooling

Buffer gas cell

Towards ultra-cold molecules

Lowest temperature of “real molecule” is currently tens of uK (ultra-cold atom experiment few nK)

Ultra-cold molecules would allow:
- Extremely precise transition energy measurement
- Discovery of new physics based on low-energy scale experiments
- Precise sensors to external fields
- Quantum simulation with long-range interaction
Conclusioni

- Le tecnologie quantistiche possono essere utilizzate per lo sviluppo di strumenti sia per impieghi in fisica fondamentale sia per applicazioni tecnologiche.

- Le recenti attività/sigle di gruppo 5 nate da esperimenti «quantum» di gruppo 2 (e non solo) mostra come sia presente la volontà da parte dei gruppi di ricerca in sezione di rendere fattuale tale trasferimento tecnologico.

GRAZIE DELL’ATTENZIONE!