<u>Minutes of the RDq / DRD5 workshop April 3-6</u>

These are the minutes of the closed workshop that took place at CERN on April 3-6, 2023, and whose goal it was to reflect both the ideas and concepts on quantum sensors for particle physics in line with the ECFA detector R&D roadmap, that were submitted in response to a request to a large number of individuals in the wider community that had been involved in prior symposia on quantum technologies for particle physics, but also to build on the networks of the conveners themselves.

Over three dozen submissions were received and discussed among the conveners of the relevant specific quantum sensing family before the workshop, who then incorporated these in different formats into their overviews. It was reconfirmed that the *goal of the workshop* would be to identify potential candidate areas that could constitute the seeds of the work packages of the LOI and subsequently of the proposal to be submitted by the *future DRD5/RDq collaboration*. These minutes highlight some of the discussed possible seeds in red. This document comprises the minutes of a 3-day long discussion, so can only partially reflect the full range of contributions and topics that were touched upon.

Because of the wish to have a very open discussion at the workshop and in recognition of the fact that very different communities were considered in the course of the discussion, the presentations themselves will not be publically available, but instead, it will be left up to the individual conveners to decide which parts of their presentations they wish to share within their communities. On the contrary, the White Paper that will result from this workshop on a short time scale will be public and open to comments and contributions, as will the LOI, the open symposium at CERN from October 2-4 and the proposal.

The following conveners were involved:

Etiennette Auffray, Caterina Braggio, Florian Brunbauer, Shion Chen, Martino Calvo, Marcel Demarteau, Michael Doser, Christophe Dujardin, Andrew Geraci, Arindam Ghosh, Glen Harris, David Hume, Derek Jackson, Jeroen Koelemeij, Georgy Kornakov, Stefan Maier, Alberto Marino, Tanja Mehlstäubler, Alessandro Monfardini, Ben Ohayon, Nancy Paul, Sadiq Rangwala, Florian Reindl, Mariana Safronova, Swati Singh, Stafford Withington, Steven Worm

______________________________ workshop schedule ________________________________

Monday: atomic clocks, clock networks; legal aspects

Tuesday morning: superconducting and spin-based sensors

Tuesday afternoon: kinetic detectors; IP aspects

Wednesday morning: atoms, ions, molecules and atom interferometry

Wednesday afternoon: optomechanical sensors; collaborative aspects; international context

Thursday morning: metamaterials, 0-, 1-, 2-dimensional materials; next steps towards LOI

<u>Monday, April 3:</u> (atomic clocks, clock networks)

Steven Worm: Introduction to dark matter, explains how different systems can have different sensitivities, to a wide range of possibly existing physics.

Dave Hume: talks of clocks, and what / how they operate, what the role of femtosecond lasers are. Want to measure a frequency ratio (unitless, transportable, can be differentially sensitive to symmetries/fundamental constants). Multiple sites (at NIST/JILA) connected via fiber, direct optical link. Need to use dedicated stabilized optical link (air turbulence, vibrations will degrade stability). Discusses a scheme to measure the noise in transfer - requires fully bi-directional operation (network providers don't necessarily have the bidirectional amplifiers, needed every ~ 80 km).

Tanja Mehlstaeubler: talks clock comparison and state-of-the art in putting spectroscopic bounds on a possible variation of alpha, dark matter mass ranges and coupling constants to ultra-light matter and limits to a violation of LLI. The currently most sensitive clock operational in laboratories is the Yb+ ion clock, but knowledge of bounds of Standard Model physics and DM coupling constants can only be obtained in clock comparison with other clocks and species. Global monitoring will allow for insight in temporal and spatial variations. Steven: short overview of results with Cf ions. Some submissions, conveners know many active groups. Highest density of ultra-precise clocks is currently seen in Europe, but a current undergoing world-wide effort pushes also multiple clock developments at highest level in Asia and America.

Physics aims: search for light bosonic dark matter, variation of fundamental constants, precision measurements of alpha or mu, Lorentz invariance.

Submission 1: network of ultra-precise clocks based on different systems/couplings = possible work package. Such an effort goes well beyond the ability of a single institution. Builds on existing design study (CLOck NETwork Services) to go beyond current single point-to-point connections between a small number of partners, mainly relying on national initiatives. Excellent case for cross-national collaborative effort to get a higher value out of the individual parts. Addressing technical issues (HW for L-band needs to be developed, test dedicated (dark) and existing LCG network fibers, switching bands between countries at borders (cross-border links)) can form part of the milestones / sub-WP's.

Submission 2: Transportable optical clock for reference (cheap, reliable, compact, simple to operate), solves challenge of how to link clocks at the global scale (rather than continental scale) = possible work package.

Further proposals were also discussed and can be considered in a later phase. The question of the balance between "engineering" and "organizational" challenges is particularly salient in this case.

Structure the WP's such that first technical steps lay the groundwork with a larger long-term vision to aim for.

Legal aspects: presentation by Nicolas Houet from CERN legal office: presents the different structures that a Memorandum of Understanding (MOU) with CERN can encompass, there appear to be a number of roughly similar constructs to what we have in mind; we can use those as starting point when setting up an MOU for RDq. In the context of the other task forces of the ECFA roadmap, a new concept of a Memorandum of Agreement was floated, but it was not clear to Nicolas what that concept consists of, nor what it entails.

Tuesday, April 4: morning: (superconducting and spin-based sensors**)**

Shion Chen: talks about: superconducting qubits / link to HEP. Super-cooled LC circuit has ground state, 1 excited state with strong E-field sensitivity, long coherence time, scalable(...). Junction is 200 nm x 200 nm. Energy split ~ microwave: wave-like DM, axions, HF gravitational waves.

In attempting to identify potential work packages, a number of sensitivity bottlenecks were considered (access to nanofab farm, dilution fridge, very rapid progress within industry, the impact of background radiation from cosmics, engineering and modeling of devices into systems). Further directions involve reaching lower temperatures via nuclear demagnetization fridge, with goal of 1mK operation (thermal excitation suppression), B-field resilience, or cavity optimization. Among these, B-field (e.g. multi-T) resistant qubits were considered a promising possible work package.

Derek Kimball: discusses three overarching possibilities for spin-based detectors:
- levitated ferromagnetic torque sensors (overlaps with spinor BEC and optomechanical accelerometer)
- molecules with radioisotopes for eEDM
- large volume, high density, highly spin-polarized samples (for HEP and exotic spin-dependent samples)

1) sensitive to local sources OR ultra-low energy bosonic field [PRAppl. 13 (2020) 064027].
Spin samples with long coherence times such as ferromagnetic particles (10 micron particulates floated in vacuum at 10 mK) should be many orders of magnitude more sensitive than existing systems (e.g. NVD, BEC). Consortium of groups in Europe and US collaborators exists (some funding from Quantera, others unfunded). Arrays of these micro-particulates should be possible.

State-of-the-art (superconducting) R/O electronics, much better vacuum, purity/flux trapping of superconductors needed for suspending: these are the kinds of tech developments needed and are areas where the community and CERN has a lot of expertise = possible work package

2) Molecules with radionuclides for eEDM searches: reach in terms of SUSY sensitivity beyond 10 TeV (even 50 TeV ?) masses. Needed: improvements to existing experiments, new trapping technologies, advanced quantum control of molecules, offline access to species of interest, harvesting & handling on ~1 day time scale. There are ongoing efforts at ISOLDE, TRIUMF, FRIB. "Beam to beaker to beam" -> portable Penning traps / Paul traps with XUHV.

3) production of polarized "targets" *and* CASPEr - like experiments benefit from large compact samples of spin polarized nuclei. Need to go to lower temperatures (4K->10mK), larger sample size(mm -> 10 cm). Looking at and need to develop (for nuclear spin polarization): para-hydrogen production-> other species; dynamic nuclear polarization (CASPEr-E with ferroelectric crystals).

Optical polarization, polarized lXe, lHe3, naphthalene, ... in many cases, this requires advances in Solid state physics, chemistry, etc., so there is a need to enable supporting developments.
In this context, the usefulness of bulk polarized materials (such as NVD) for helicity-sensitive tracking devices, relevant also for nuclear physics, was underlined by *Georgy Kornakov*. R&D needed on hyper-polarization., beam tests for proof-of-principle.

Caterina Braggio: big interest in haloscope community to operate sensors "at a distance" - limited collaboration between small groups on read-out: not clear whether larger collaborative efforts would be helpful.
Two promising research directions:
- transmon qubits readout (Single microwave photon detectors for cavity readout)
- single current-biased Josephson junction
Both are narrow bandwidth, while tunability of device and R/O desirable. Design needs to be modified / superconducting circuit more complex. Areas where one could benefit: dark count rate, going beyond linear amplifiers, scan rates. Can these efforts benefit from a consortium-like structure like RDq?

Hiroki Akamatsu: presents overview of superconducting photon detectors:
a) 100 mK KID for HEP detection: (70 keV photons)
b) optical photons via TES (0.2~10 keV), 2 order of magnitude better resolution (1.6 eV) than standard x-ray detectors, but slow (100 us). R/O challenges. Users would be keV x-ray spectroscopy (e.g. of muonic atoms isolated in vacuum with TES), searches for milli-charged particles (TES array stacks for milli-charged trackers, using high-Tc superconductors).
There is mature work in space instrumentation: opportunity for port to particle physics. KEK has started a "QUD" initiative to work on these KID, TES microcalorimeters and photon detectors.
There is interest within existing TES communities in overlapping activities with RDq.

A possible WP could focus on TES systems, integration, high temperature TES, including cryo-electronics.

Tuesday, April 4: afternoon: kinetic detectors

Stafford Withington: focus on developing a technology base (with biggest impacts on many)
Superconducting tech essential for observational astronomy. Next gen telescopes in IR~mm, but also x-ray. Not just single (kilo-pixel) detectors but also complex superconducting electronics. Engineering of superconducting materials to control Tc, but also their other properties (e.g. bi-layers, multi-layers). Very high vacuum is essential for the UHV sputtering processes, as are a number of further performance characteristics of any resulting device. Focuses on the intermediate TRL developments.

Technologies needed:
- single photon detection (incl. at microwave frequencies)
- ultra-low-noise amplifiers, high temp (4K) ultra-low-noise amplifiers, chip-based systems for generation and detection of squeezed states over microwave to mm wave range.
- solid state superconducting detectors for high-energy photon and massive particle detection and spectroscopy, such as single-electron detection
- development of packaging methods for superconducting electronics (e.g. magnetic field shielding, cosmic ray shielding, stray light shielding, EMI, ...)
- multiplexing technology challenges for superconducting mega-pixel devices
- materials science challenges

These can be grouped into three areas:
Theme 1: superconducting electronics for microwave-mm-wave range
Theme 2: high-energy particle detection (photons & massive particles)
Theme 3: characterization and measurement methods (including packaging and screening techniques to stop photons reaching the detector) - industry won't develop this because of development /

customization costs.

Generally: coordination / collaboration needed, although some work is already ongoing (e.g. Fermilab with standardized packages). Cost estimate: 30 M€ level.

Single out parametrizable amplifiers? Challenges: integrated superconducting filters, circulators (can this be done in on-chip superconducting thin films?).
In any case, a list of specific milestones will need to be defined as intermediate stepping stones to the long term visions of the other presentations earlier. WP's may well cross family boundaries.

Alessandro Monfardini / Martino Calvo: KID arrays - long-range athermal ballistic phonons to detect charged particles. First application: CALDER experiment for Cerenkov light. Then: WiFiKID's: contact-less coupling of contactless KID to read-out line: x-ray detection. Propose this approach for multiplexing. Complementary to thermal detectors/bolometers for DM detection. There is an international collaboration to develop KID R/O, but this is now diverging (application specific).
Rome group working on single particle detection. UK working on TES electron spectroscopy. Multi-k pixel arrays should be possible on 12" wafers (à la BULLKID). Threshold (1 sigma) = 20 eV. Bolometers have better resolution... but the real strength is high mass, highly segmented device.
WP's: Stafford volunteers, with input from Marcel & Michael to formulate a number of key activities / Need to look at synergies ...

IP issues: presentation by *Benjamin Frisch*: introduction into different aspects of IP, issues that can arise. General recommendation to think through issues such as patents, interaction with industry, licensing, sharing of IP (prior, created during collaboration, after a group leaves).

Wednesday, April 5: morning: atoms, ions, molecules and atom interferometry

Ben Ohayon: differentiates between simple, accurate systems; and sensitive, precise systems (clocks, magnetometers, atom interferometers, RMP 90. 025008 (2018))
- Sensitive systems: very sensitive to ultra-light DM, suited to eEDM (measuring zero to very high sensitivity).
- Simple systems: H, D, Hbar, He^+ Rydberg constant, geared to Rydberg, Alpha, masses, QED tests, nuclear corrections, fundamental constants. Much interplay between areas.
Arxiv.2210.16929 for example of interplay , also PRL 130 (2023) 121801.

Nancy Paul: strong field QED (> 10^{12} V/cm] (H-like U^{91+}) vs low field QED [<10^{11} V/cm] (H).
"Spectroscopy" of H-like U^{91+} requires accelerator infrastructures, far beyond laser spectroscopy, nuclear effects ~ strong field effects. Exotic atoms: transitions between Rydberg states show pure strong-field effects. Potential of antiprotonic / exotic atoms also for direct DM searches, millicharged particles (via effect on bound states). Quantum sensors needed for precision spectroscopy in X-ray regime: TES microcalorimeter has $\Delta(E)/E \sim 10^{-4}$. Magnetic microcalorimeters (better linearity) are complementary. Cheaper refrigerators would be highly impactful.
Calibration needs to bracket lines of interest closely, pixel by pixel. A global effort (to sub-ppm) on reference lines would benefit many communities. Needs both improved measurements as well as new systems (HCI's, exotic atoms as references lines). Improvements have impact beyond exotic atoms:

Submissions cover:
- Rydberg blockade between Hydrogen and Antihydrogen atoms (*Sadiq Rangwalla)*
- trapping/cooling of antihydrogen (ions) in an ion crystal for gravity
- quantum beam tracker (trapped atom quantum state visualizer) - non-destructive beam position visualizer; similar to imaging an ion beam with a BEC (around 2010
- eEDM and pEDM
- atom interferometry: entangled atom interferometry in an entangled spinor BEC
- large-scale atom interferometry

A WP could be a "Muasty"-like focus on a theoretical & experimental approach combining QED, nuclear, Rydberg theorists into the study of the exotic atom and ion systems.

Such a WP would fall into sub-WP's / milestones:
- a dedicated theory collaboration that would be closely linked to the atomic physics community, metrology, and that would inform future experiments on exotic systems
- device fabrications (TES's, R/O) microcalorimetry - overlap with CMB, neutrino
- g-factor measurements (on H-like systems in traps), radioactive H-like systems, HCI in Penning traps, HCI clocks, and thus a focus on trapping/manipulating/observing HCI's in traps?
- portable traps
- Development of a community device, where detectors can be easily swapped in and out?

Many discussions also on atom interferometers (Sadiq, AION, DM, Hbar fountain, ...) that cover a very wide range of activities but for which it is difficult to identify common challenges. Nevertheless, precision measurements for fundamental physics are actively being pursued in AMO, and a corresponding WP would be very welcome; similarly, strong interest in Exotic systems in traps and beams

Wednesday, April 5: afternoon: optomechanical sensors

Andy Geraci: overview of submissions; sensing methods; roadmap/discussion of harmonic oscillators, limited by thermal noise, shot noise, back action and arrays of networked sensors

- 13 submissions, in 3 classes:
  - superfluids, liquid He
  - bulk/clamped optomechanical (trampoline,
  - suspended particles/objects

Searches for: wave-like DM, extended DM, quantum effects, fundamental symmetries, other (millicharged particles, chameleons). Many would benefit from an integrated network.
• Cavity-based sensors: DM fields can change alpha -> time-dependent oscillating component -> Bohr radius oscillates as a function of time -> compare length of two cavities (rigid vs. suspended)
• networks can greatly improve sensitivity/range/identify correlations
• link to GW searches / DM at the upper mass end of the DM range (primordial BH's, axions)
• suspended particle(s) in cavity / better than LIGO at high frequencies / DM à la Windchime
• one submission: micromechanical torsion balance / fifth force tests
• role of gravity in quantum entanglement

All of these are at different stages of maturity. Many if not all could still benefit from dedicated R&D. Integration / networking would be highly useful. Need to identify key common research priorities.

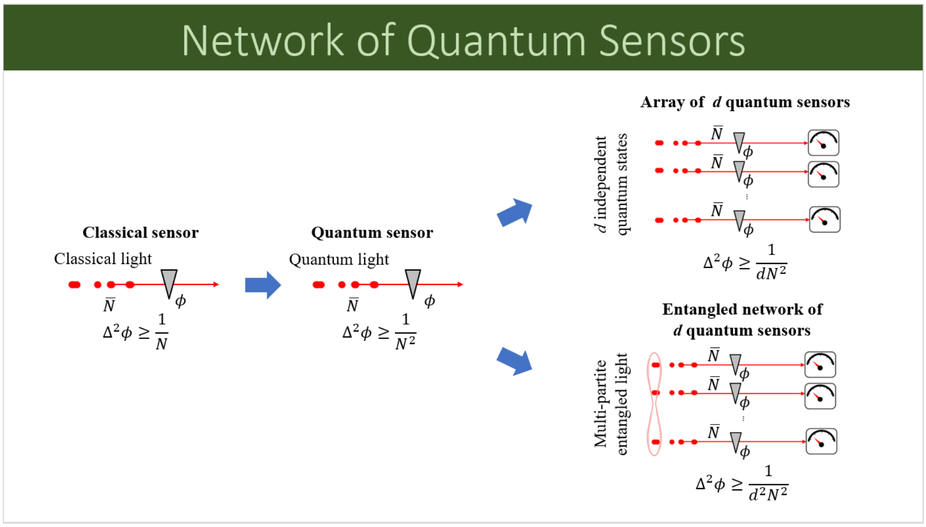
Swati Singh: expands on above, addresses a few specific submissions:
LHe: tunable resonant mass detector, very low acoustic losses
Multiple existing mechanical approaches, but would benefit from improved networking.

Glen Harris: superfluid opto-mechanics for DM detection

Phonon/photon/quasi-particle production in lHe through recoil, pick up signal via bolometers in lHe or above it. To expand on limited sensitivity, transform acoustic excitations (energies of micro-eV) into eV photons (detect with SNSPD).
Need to expand quality of cavities, SNSPD's; several labs have particular expertise, but no coherent effort on these developments. Getting heat in mirrors down is a challenge.

This idea overlaps with HeLIOS (acoustic motion), high frequency gravitational waves, superfluid DM detection; could be merged into a larger LOI around superfluid lHe
There are links to neutrino scattering/detection, very low energy recoil, CEvNS ?

Alberto Marino: arrays of sensors (large numbers: ~ 10^8~10^9), for a size of ~ 1m^3 to achieve sensitivities needed for detection of DM through gravitational interactions. Arrays would also benefit measurements of other weak forces/interactions.
Demonstrates the impact of using squeezed light that results in much enhanced S:N
Entangling sensors also gets you an improvement (scales with number of entangled sensors)



The resulting discussion focuses on DM as a common theme, although there is a wide diversity of technologies. It is not yet clear which technology would be most beneficial to focus on:
making better squeezed light sources (would benefit everybody), transduction interrogation techniques, global time stamp distribution to better than 1ns, entanglement.

Michael Doser: structuring the collaboration: two main outcomes of the discussion: try to keep the structure as simple/compact as possible (i.e. think about merging international advisory board with Collaboration Board, or minimizing the Management board to a spokesperson + 1 representative per platform); agreement on the need to have internationally distributed "platforms" or "hubs" for organizational reasons (one per family for a total of 6), although their role needs to be defined more precisely. Interaction with industrial/commercial partners still needs refining, also regarding their voice in shaping some of the research directions.

Marcel Demarteau: overview of quantum sensing related developments taking place in the US

Tomohiro Inada: provides a very interesting overview of quantum sensing activities at Xinhua and other universities in China; in total, around 1000 researchers in this field, spread mainly between three institutes.

Thursday, April 6: metamaterials, 0-, 1-, 2-dimensional materials

Christophe Dujardin: quantum sensing in this field is related to nanoengineering

Quantum dots: confinement results in artificial atom, nanowires, nano-platelets. Changing energy levels, can be used as single photon emitters, used in e.g. Neutrino observatories or double-beta decay searches. These structures allow for e.g. directional emission (NuDot, or from carbon nanotubes) and ultrafast photon emisson (200 fs).
Chromatic dispersion in nano-platelets: FWHM: 9nm, only defined by thickness, not by lateral size (contrary to quantum dots). 2-d perovskites consisting of alternating layers of halogen ions linked by organic compounds are also being investigated.

Stopping power is important for HEP, so Micro-machining / engineering of a mix of bulk & nano-materials is required. Discusses metalenses, other nano-structured materials (metal organic frameworks = MOF), aerogel / scintillators (e.g. YAG aerogel, high porosity, scintillators to detect e.g. tritium, but also dual mode Cerenkov detectors), super-crystals (scintillating ~250 nm scintillating sphere for optically suspended nano-spheres; HfO2-loaded water (density ~ 3 x water)),
CdSe quantum dots for neutrinoless double beta decay

Florian Brunbauer: graphene monolayers on photocathodes increase work function (WF) = enhances emissivity, while BN decreases WF, increases QE. Mono-layer and Bi-layer in GEM's to reduce ion backflow. Twisted bi-layer graphene is tunable, very low heat capacity (very sensitive to long wavelength photons)

Arindam Ghosh: both 2-D materials and quantum dots are being looked at in India. Examples are:
• WS_2 monolayers + PMMA reflectors; WS_2 - graphene heterostructures to go beyond Si, HPGe semiconductor technologies. These result in very high electron mobility (micron-scale) graphene FET devices. MoS_2 added in also greatly reduces noise.
• Nitride semiconductors as scintillating devices to detect neutrons via n+^14_7N ->p + ^14_6C . (High-energy proton-induced electron hole pairs).
• Rb-atom-based "Single-shot high precision magnetometry w/ long-lived quantum memories"
• Graphene-based optomechanical devices
• NV-diamond based calorimetry, 2D microwave bolometry, combine with defect calorimetry (above), combine with atomic magnetometry.

WP discussion: this field is very, very broad, with many individual areas. When looking at common challenges, a large number of possibilities were looked into, and the most general commonality that emerged was the benefit of a way to evaluate the usefulness of specific developments: a possible WP would thus be screening of materials and devices in a systematic / standardized manner (which can include testing samples with minimum ionizing radiation, a platform for sharing/exchanging information between producers and detector designers.

Developments are already under way for the integration of heterogeneous heterostructures:
Arindam: one goal is to produce 1 M heterodyne transistors in the framework of the Indian quantum initiative (national mission), and a "platform" is being set up to facilitate this, to bring together a number a different potentially interested groups.

Two further possible WP areas are in the field of quantum dots (perovskites, quantum wells) as scintillator components, and engineered multi-2D-layer structures (e.g. graphene heterostructures, bolometry, ...).

<u>next steps & timeline until submission of proposal end 2023:</u>

<u>Immediately</u>: Make minutes available to conveners by mid-next week [week of April 10].

The minutes are foreseen to be made public as soon as the conveners have incorporated their feedback. This is just a short working document for letting the communities know what is going on, and what is being discussed.

+2 weeks: cook a "white paper", i.e. de facto an intro + a list of proto-WP's (Marcel, Steven, Stafford, Tanja, Nancy, Georgy, ..., Michael) [week of May 1] + Circulate among conveners (~2 weeks)

<u>Then</u>: make White Paper public [week of May 16], collect additional input for 1 month; workload will be on conveners to interact in their areas with the individuals/groups contacting them and reflect these inputs in the LOI that will be closely based on the white paper.

until mid/end June: write draft LOI (2-4 weeks)

Mid/end June: circulate draft LOI widely for refining and to allow groups to indicate their interest for signing up to the process (2-4 weeks) - <u>it will be clearly spelled out that signing up is in no way a commitment, but rather an expression of interest.</u>

end July: *<u>submit LOI to DRDC</u>*

[start work on proposal, circulate amongst conveners, to be ready for symposium]

<u>October (2-4): *open symposium at CERN*</u>: polish the proposal so that it takes into account the feedback from DRDC, ECFA, signatories to LOI, symposium and allows further groups to refine & sign up.

December: *<u>submit proposal to DRDC</u>*