Bureau International des Poids et Mesures

Summary of the BIPM Workshop on

"The Quantum Revolution in Metrology"

held at the BIPM on 28th and 29th September 2017

This summary report was prepared by Dr Carl Williams (NIST) and Dr. Angela Gamouras (NRC), and reviewed by the steering committee of the workshop.

The BIPM Workshop on "The Quantum Revolution in Metrology" had 137 participants from 40 National Metrology Institutes (NMIs), universities, and research laboratories representing 27 countries.

The workshop included five oral sessions including 23 speakers covering:

- Single photon measurements, radiometry with entangled sources, superconducting particle detectors
- Quantum standards for mass, pressure, vacuum, temperature, acoustics and vibration
- Highly entangled systems for metrology, entangled optical clocks
- Advances in quantum electrical standards, single electron transistors and demonstrations of the "quantum metrology triangle
- Beyond quantum metrology

The first four sessions included excellent overviews of the underlying metrology area from a leading NMI. The meeting also included 2 poster sessions with 56 posters.

The meeting highlighted improvements in the field as well as objectives for future advancements involving quantum metrology applications. Two of the fields – *electrical metrology* and *atomic clocks* – have been around for more than 25 and 50 years respectively. Indeed, atomic clocks have made increasing use of Norman Ramsey's quantum state superposition technique of separated fields to enhance resolution over the last few decades. However, these two areas are far from static and are evolving at a rapid pace.
Overcoming the quantum projection noise limit in optical clocks based on single or large numbers of trapped atoms can involve entanglement or spin squeezing techniques. Distributed entangled clocks may one day provide methods for detecting gravity waves and dark matter – thereby helping to probe the universe. Additionally, as these clocks further improve they will lead to relativistic geodesy and significant improvement in tectonic geodesy. The latter may one day allow improvement in earthquake prediction.

For *electrical standards*, there have been many efforts to close the quantum metrology triangle which serves as a consistency test between three quantum electrical effects: the Josephson

Effect, the quantum Hall effect, and the single-electron transport effect. The quantum Hall effect in graphene shows strong promise for resistance standards as a higher temperature and lower magnetic field are required for measurements, but long-term stability needs to be developed. In the future, it may be possible to integrate two or more of these components into a single chip allowing a single chip to provide traceable electrical metrology.

In the field of *quantum optical metrology by photons*, there is a need for further development of metrics and characterization methods for single-photon sources and detectors. The field is advancing rapidly and efforts have begun to explore their application to fields like quantum communication and bio-imaging. Efforts among NMIs around the world are underway to use this technology to provide a firmer foundation for the candela.

Advances in *quantum standards for mass, temperature, and gravity* based on portable and robust instrumentation, as well as primary ultra-high vacuum and extreme-high vacuum pressure standards based on ultra-cold atoms are developing rapidly. In the case of pressure and temperature new standards are now competitive with the best standards owned by NMIs.

Further applications of quantum technologies include the implementation of superconducting quantum interference devices in various fields such as in specialized bio-magnetic measurement systems to quantify human perception, in nanoscale measurements including magnetization metrology of nano-magnetic particles, as well as in the controlled implantation of a single ion for spin-flip detection.

Looking forward, the future implications of quantum-based technologies for NMIs will be a shift from artifact-based calibrations. Quantum metrology provides the means to create inherent quantum standards (like our electrical standards and atomic clocks) that may require validation or intercomparison but will be a direct realization of a unit of the revised International System of Units (SI) based on fundamental constants. As a result, these standards will be absolute standards ensuring consistent precision when realizing the units. Leading NMIs have been and are continuing to evolve from classical ways of defining the SI measurement units to a quantum way. This will allow NMIs to better disseminate the SI and create a world where many people will have access to world-class metrology.

Finally, quantum metrology is beginning to take advantage of quantum effects to enhance precision beyond that possible through classical approaches. By using some of the *stranger properties of quantum mechanics*, it is possible to make high-resolution and highly sensitive measurements of physical parameters beyond the shot noise or single quantum limit. The result is that we exploit quanta and individual packets of energy not only to set the standard but to be manipulated in a manner that provides for higher precision realization of the underlying unit of measurement. This radical departure together with these new quantum standards will significantly change the existing approach to traditional measurement concepts and necessitate a reappraisal of how we provide traceability.