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List of key parameters of the experiments to enable tests

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INTRODUCTION

This document looks at a selection of ten space mission proposals which aim at exploiting the unique conditions of space and satellite platforms to perform fundamental physics. We extract lists of key parameters for experiments based on atomic, optomechanical and photonic systems to put different experiments on a somewhat common footing.

IMPLEMENTATION

Our aim in this document is to list the key parameters that are required by each mission to fulfil its purpose. Necessity dictates that this text is not to be seen as comprehensive; rather, our aim is to outline the state of the art as presented by a selection of key experiments and studies.

The studies were selected after discussions during QTSpace working group meetings, in particular the meetings … where the following topics were discussed:

Atomic systems

In Table 1 we outline several parameters that atomic systems in space must fulfil in order to explore fundamental physics. In an effort to capture the state of the art, we have chosen to highlight the following proposals:

BECCAL (Bose-Einstein Condensate and Cold Atom Laboratory, [1]) is a new NASA-DLR founded multi-user facility capable of performing experiments with Rubidium and Potassium cold atoms and Bose Einstein Condensates aboard the ISS.

STE-QUEST (Space-Time Explorer and Quantum Equivalence Principle Space Test, [2]) is a proposal for an ESA mission for atomic interferometer with atomic clocks for testing the validity of the Einstein Equivalence Principle.

AEDGE (Atomic Experiment for Dark Matter and Gravity Exploration, [3]) is a proposal for a mission for probing dark matter and gravitational-wave measurements through the use of atom interferometry.

SAGE (Space Atomic Gravity Explorer, [4]) is a proposal for a multipurpose mission employing atom interferometry for observing gravitational waves, dark matter, possible violations of Einstein Equivalence Principle and Bell inequalities.

	BECCAL [1]	**STE-QUEST [2]**	**AEDGE [3]**	**SAGE [4]**
Size of superposition	$\sim 10^{-1}$ m		< 0.9 m	
Interferometer times	≥ 10 s		300 s	
Trapping frequencies	< 1 Hz			
Flux of atoms	$10^{7} - 10^{9}\ \mathrm{s}^{-1}$			
Atom species	Rb, K			Sr
Number of atoms	$10^{4} - 10^{6}$			7×10^{6}
Expansion velocity	$\leq 100\ \mu\mathrm{m\ s}^{-1}$			
Atom temperature				20 pK
Interferometer contrast	$< 0.2\%$			
Rabi frequency	≥ 10 kHz			60 Hz
Imaging resolution	$\leq 10\ \mu$m			
Vacuum	10^{-10} mbar			
Comparison of ground clocks		10^{-18}		
Space-to-ground time transfer accuracy		< 50 ps		
Synchronisation of ground clocks		< 50 ps		
Atomic time scale		$< 10^{-16}$		
Differential geopotential measurements		$0.15\ \mathrm{m}^{2}\ \mathrm{s}^{-2}$		
Detector baseline			4.4×10^{7} m	2×10^{9} m
Phase noise			$10^{-5}/\sqrt{\mathrm{Hz}}$	$10^{-3}\ \mathrm{rad}/\sqrt{\mathrm{Hz}}$
Number of pulses			1000	7
Strain sensitivity				$3 \times 10^{-20}/\sqrt{\mathrm{Hz}}$

Table 1. Summary of key parameters required to realise a selection of space-based fundamental physics experiments that use atoms. Data from Refs. [1]–[4]; empty cells denote data that is either unavailable or not relevant to the experiment in question.

Photonic systems

As regards photonic systems, Table 2 outlines the key parameters identified by a number of studies for enabling fundamental physics experiments in space. To capture a broad snapshot of the state of the art we have chosen to highlight the following proposals:

Space QUEST (Space—Quantum Entanglement Space Test, [5]) is a proposal for quantum communication between ISS and ground, which will study decoherence in an entangled photonic system.

LISA (Laser Interferometer Space Antenna, [6]) is a proposal for a large-scale spaceborne optical interferometer to detect gravitational waves.

CQuCoM (CubeSat Quantum Communications Mission, [7]) is a proposal for quantum communication between CubeSats and ground, which will study decoherence in an entangled photonic system.

QEYSSat (Quantum Encryption and Science Satellite, [8]) aims to test quantum key distribution and quantum entanglement sciences using a quantum receiver in space.

Nanobob [9] is a proposal for quantum communication between CubeSats and ground in an uplink configuration. It will study decoherence in an entangled photonic system.

	Space QUEST [5]	LISA [6]	CQuCoM [7]	QEYSSat [8]	Nanobob [9]
Wavelength	830 nm			670 nm	
Ground diameter	13 cm		1 m	50 cm	1 m
Receiver diameter	24 cm	30 cm	10 cm	10–30 cm	15 cm
Angular error	15 μrad	≤ 10 nrad	≤ 1°	2 μrad	10 μrad
Platform	ISS	Heliocentric satellite	Cube-sat		
Altitude	408 km	2.5 Gm	500 km	600 km	550 km
Losses	≥ -46 dB		≥ -40 dB		
Source rate (single)	350 MHz			300 MHz	
Source rate (pair)	350 MHz			100 MHz	100–300 MHz
Received photon rate	$19500\ \mathrm{s}^{-1}$				
Received pair rate	$2650\ \mathrm{s}^{-1}$				

Table 2. Summary of key parameters required to realise a selection of space-based fundamental physics experiments that use electromagnetic radiation. Data from Refs. [5]–[9]; empty cells denote data that is either unavailable or not relevant to the experiment in question.

Massive objects and optomechanical systems

MAQRO (MAcroscopic Quantum ResOnators, [12]-[12]) is the only proposal, to the best of our knowledge, which aims to use the unique properties of a space environment to perform tests of the foundations of quantum physics, to explore decoherence mechanisms and the boundary between quantum and classical worlds with interferometric and non-interferometric techniques. The experiments suggested to be performed in MAQRO aim to use high-mass test particles with masses up to 10^{11} atomic mass units (AMUs).

Following ESA's call for New Science Ideas, the feasibility of implementing MAQRO-type experiments in a space-mission was investigated in detail in the QPPF (quantum physics platform) engineering study at ESA's Concurrent Design Facility in 2018 [13].

	MAQRO [11]	**QPPF [13]**
Size of superposition	$\lesssim 10^{-3}$ m	$< 10^{-3}$ m
Particle mass	$< 10^{11}$ amu	$\leq 5 \times 10^{9}$
Interferometer times	≤ 100 s	≤ 40 s
Trapping frequencies	10^{3} Hz $- 10^{5}$ Hz	10^{3} Hz $- 10^{5}$ Hz
Particle material	Fused silica, diamond, silicon, …	
Number of atoms	$10^{9} - 10^{12}$	$10^{9} - 10^{11}$
Expansion velocity	≤ 11 μm s^{-1}	≤ 11 μm s^{-1}
Particle temperature	<25K	<25K
Environment temp.	≤ 20 K	≤ 20 K
Imaging resolution	< 1 μm	< 1 μm
Vacuum	10^{-15} mbar	10^{-13} mbar

Table 3. Summary of key parameters required to realise a selection of space-based fundamental tests using high-mass particles. Data from Refs. [10]-[13].

CONCLUSIONS

We have selected a number of studies that explore the requirements and possible outcomes for space missions to test fundamental physics. Broadly speaking there are three kinds of platforms we considered: atoms [1]–[4], photons [5]–[9], and massive objects and optomechanics [10]-[13]. The key parameters have been selected and reported in Tables 1 - 3.

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