How cold can you get in space? Quantum physics at cryogenic temperatures in space

Gerald Hechenblaikner\textsuperscript{1}, Fabian Hufgard\textsuperscript{1}, Johannes Burkhardt\textsuperscript{1}, Nikolai Kiesel\textsuperscript{2}, Ulrich Johann\textsuperscript{1}, Markus Aspelmeyer\textsuperscript{2} and Rainer Kaltenbaek\textsuperscript{2,3}  
\textsuperscript{1} EADS Astrium, D-88039 Friedrichshafen, Germany  
\textsuperscript{2} Vienna Center for Quantum Science and Technology, Faculty of Physics, University of Vienna, Vienna, Austria  
E-mail: rainer.kaltenbaek@univie.ac.at

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Abstract
Although it is often believed that the coldness of space is ideally suited for performing measurements at cryogenic temperatures, this must be regarded with caution for two reasons: firstly, the sensitive instrument must be completely shielded from the strong solar radiation and therefore, e.g., either be placed inside a satellite or externally on the satellite’s shaded side. Secondly, any platform hosting such an experiment in space generally provides an environment close to room temperature for the accommodated equipment. To obtain cryogenic temperatures without active cooling, one must isolate the instrument from radiative and conductive heat exchange with the platform as well as possible. We perform analyses on the limits of this passive cooling method for a recently proposed experiment to observe the decoherence of quantum superpositions of massive objects. In this context, we obtain temperatures of 27 K for the optical bench and 16 K for the critical experimental volume. Our analyses and conclusions can readily be applied to similar science experiments requiring a cryogenic environment in space.
1. Introduction

Experiments often require isolating the object under investigation from its environment. This holds true in particular for quantum experiments, where any information shared with the environment may decohere the quantum state and disturb its evolution in time. Free and undisturbed evolution in time is, however, an essential prerequisite in many quantum experiments, and it is even more important, when the laws of quantum physics themselves shall be put to the test.

Consider a physical system left alone in outer space far from any other objects. This is probably the situation closest to absolute isolation we can imagine. Would we be able to completely describe the evolution of the system in terms of quantum physics? Maybe not. For example, spatial superpositions of massive objects might behave unexpectedly due to the yet unclear role of gravity in the context of quantum physics. A number of modifications to quantum theory have been suggested that predict decoherence of massive quantum superpositions even for completely isolated systems. Among such proposed theoretical extensions of standard quantum theory are the ‘macrorealistic’ models of Diósi [1], Penrose [2], Károlyházy [3], the continuous-spontaneous-localization (CSL) model [4–6] and the quantum-gravity model of Ellis et al [7]. A detailed overview of such models and of experiments testing them is given in [8, 9]. Examples of Earth-based experiments toward realizing macroscopic quantum superpositions are [10, 11] using photon states, [12, 13] using superconducting loops [14], using spin-squeezed atomic ensembles and [15, 16] using molecules made up from a large number of atoms.

Naturally, no experiment will be able to realize the idealized situation described above—first and foremost, because a completely isolated particle can neither be prepared nor measured and thus cannot be used to test our predictions. However, we can ask how close we can get to this situation. Whereas Earth-bound experiments have the natural limitation that free-fall experiments cannot be continued over very long times, this limitation is lifted when going to space. In this paper, we analyze design provisions for optimal thermal isolation of an experimental platform accommodated externally to a spacecraft. Specifically, we focus on the thermal isolation of a non-tangible, evacuated test volume surrounding a massive test particle from the hot spacecraft surface by appropriate thermal shielding. We aim to achieve a target temperature of about 30 K for the optical bench and a temperature only half as much for the isolated particle, placing us in a regime where interesting quantum effects may be observed. The corresponding optimization of the shield design is performed for the main instrument of the recently proposed ‘macroscopic quantum resonators’ (MAQRO) [17] mission that aims to test the validity of the quantum superposition principle for massive objects against modifications to quantum theory as mentioned above.

In order to derive design constraints of the thermal shield that are custom-tailored for the proposed quantum-decoherence experiments, we start with a brief summary of the MAQRO mission. We then proceed to give a detailed account of the optimization procedure for the thermal shielding that protects the experimental platform. The optimization is based on simulations that can easily be adapted to other experiments and platforms. Finally we demonstrate that the proposed design of the radiation shield indeed provides sufficient isolation of the experiment to perform meaningful tests at the foundations of quantum theory.
2. Macroscopic quantum oscillators in space

2.1. Mission design

The proposed MAQRO [17] space mission aims to explore quantum physics in yet untested parameter regimes by observing the decoherence of superpositions of macroscopic objects. MAQRO represents the inevitable next step of matter-wave experiments with more and more macroscopic objects. Over the last decades it has become evident that the free-fall times needed in such experiments would eventually require a space environment. While MAQRO aims at testing the decoherence of macroscopic superpositions, future matter-wave interferometers with massive particles will have similar requirements in terms of isolating the quantum system from the environment as well as possible. Such isolation requires:

- a low internal temperature of the quantum system to minimize decoherence due to the emission of black-body radiation,
- a low environment temperature to minimize decoherence due to the absorption and scattering of black-body radiation and
- ultra-high vacuum to prevent scattering of gas molecules by the quantum system.

Here, we will mainly consider the second requirement. In our design, using radiation shields for passive cooling, direct outgassing into space at low environment temperatures automatically leads to the fulfillment of the ultra-high-vacuum requirement. Achieving a low environment temperature is, therefore, a key requirement for the mission design.

The radiation shields and the general instrument layout presented in this paper are inspired by the design of modern cryogenic infrared telescopes which employ aggressive radiative cooling in space. Pioneering work in this field dates back to Hawarden and co-workers [18, 19], whose ideas had an important and lasting impact on the James Webb space telescope (JWST)—the history and early development of JWST are summarized in [20]—and on other missions such as Edison, Poirot and Spitzer. While all these missions employ radiative cooling to infrared space telescopes, we propose to push these concepts and technologies to their ultimate limits to allow for the implementation of novel fundamental science experiments in space. Although some of the presented design features may be specific to MAQRO, the thermal analyses and the arising design provisions are set in a broader frame, rendering our results applicable to general designs of science experiments requiring very low temperatures and the zero gravity of space.

In the past years, a number of space missions have been developed where the experimental apparatus is cooled using a reservoir of liquid helium [21, 22]. While this allows reaching cryogenic temperatures, it comes at the expense of high cost and complexity as well as a lifetime limited by the depletion of coolant. In other missions, such as those mentioned in the preceding paragraph, the coldness of space (roughly 3 K background temperature) is exploited in passive cooling concepts where the instrument faces deep-space behind a multi-layer radiation shield protecting it against solar radiation in a sun-synchronous orbit. A certain type of sun-synchronous orbit, a halo orbit around the L2-Lagrange point of the Earth–Sun system, was chosen for the JWST [23], the Herschel/Planck and Gaia missions [24], and is similarly proposed for MAQRO. This type of orbit is minimally afflicted by external perturbations and allows keeping the spacecraft stably pointed toward the Sun throughout the mission. In addition to simplifying the power and thermal architecture of the satellite, this
Figure 1. (left) CAD-model of the MAQRO instrument attached to the structural cylinder of a typical spacecraft. (right) We used a geometric surface model in the simulations for the thermal analysis.

offers optimal experimental conditions: on the one hand, simple body-mounted solar arrays can be used without need for a solar-array driving mechanism. On the other hand, excellent temperature stability is inherently provided as a result of the uniform incidence of solar flux. The central component of the MAQRO instrument is an optical bench that is accommodated externally on the shaded side of the satellite and shielded from the ‘hot’ spacecraft surface by several layers of radiation shields. The ‘warm’ electronic units of the instrument, except for the sensor, are all accommodated in the spacecraft. This architecture is illustrated schematically in figure 1 (left) using the LISA Pathfinder spacecraft [25] as a reference for an L1/L2 platform. The bench is surrounded by the innermost shield and mounted on supporting struts that are fixed to the spacecraft inner structural cylinder. Choosing the shield dimensions for the assembly to fit into the structural cylinder simplifies instrument accommodation and provides the possibility of using extensions of the cylinder as protective enclosure before the extension is discarded during commissioning.

2.2. Experimental setup

MAQRO aims at exploring the quantum-mechanical concept of superposition for massive particles. To this end, a dielectric nanosphere with a radius between 90 and 120 nm and a mass of $\sim 10^{10}$ amu is loaded from a dispensing mechanism (see figure 1 (right)) into an optical trap. The trap is formed by a Gaussian cavity mode. Once the particle is trapped, it is cooled close to the quantum mechanical ground state by a combination of cavity cooling [26–28] and feedback-cooling [29, 30]. After cooling the particle is released from the trap by switching off the optical fields. The wavefunction will then expand freely for a time on the order of 1 s. After that time, the particle is prepared in a superposition state of two positions by the action of a weak UV-pulse [31] or by using cavity-optomechanical interactions [32]. Then the superposition state is allowed to expand freely for another period of time on the order of 100 s. This is necessary for the two parts of the superposition state to overlap and form an interference pattern. In order to measure this interference pattern, the optical fields are switched on again, and the particle position along the cavity axis is measured via a combination of scattered-light imaging and cavity readout. This procedure is repeated many times over to reconstruct
Figure 2. (left) Close-up of the optical bench from figure 1. Its base-plate measures 20 cm × 20 cm × 2 cm. (right) The optical bench of LISA Pathfinder for comparison [25].

the interference pattern and to determine the interference visibility. From the latter, one can determine the decoherence rates.

A simplified representation of the layout of the optical bench (as used for thermal modeling) is presented in figure 2 (left). The optical bench is proposed to be built from components made of silicon carbide (SiC), Zerodur and fused silica. SiC is a material with a very low coefficient of thermal expansion (CTE) of significantly less than $10^{-7}$ K$^{-1}$ at very low temperatures. This type of material has also been used in the near-infrared spectrograph of the JWST [33] and in the instrument module of the Gaia mission [34]. Zerodur exhibits a very low CTE at room temperature and has been used for the optical bench of LISA Pathfinder (figure 2 (right)), where hydroxide-catalysis bonding of optical elements was successfully applied to obtain a quasi-monolithic structure of superb stability [35]. Despite the superior material properties of SiC at very low temperatures <30 K, i.e. the regime we aim for as discussed in section 3, our current model assumption for the optical bench substrate is Zerodur, which facilitates manufacture and allows using a qualified bonding process.

3. Thermal analysis for a cryogenic instrument

In the proposed instrument design, three conical thermal shields surround the optical bench in a concentric arrangement. They shield it from radiative heat exchange with the ‘hot’ exterior surface of the spacecraft (see figure 1). While the spacecraft interior is typically kept at room temperature (~300 K), as required for equipment operation, the external temperature of the shaded panel may drop as low as 120 K by effective use of multi-layer-insulation (MLI) sheets on the surface of the spacecraft. Motivated by comparison with other missions featuring primarily passively cooled cryogenic instruments, e.g. the JWST [23], we shall aim for a somewhat lower and therefore more ambitious target temperature of 30 K for our optical bench. This temperature is limited by a combination of three effects:

- radiative heat exchange by emission of thermal photons,
- conductive heat exchange through material-components (e.g. struts and wires) and
- electrical and optical dissipation on the optical bench.
The thermal analysis of the instrument was performed with ESATAN-TMS software [36], a standard European thermal analysis tool for space systems. For the purpose of numerical simulations, the instrument model was discretized into over 1000 individual elements, referred to as ‘thermal nodes’, which could individually reach different temperature values. The aim was to calculate an equilibrium state between these nodes, in which each node can be radiatively and conductively coupled to the surrounding nodes. Whereas a large number of nodes was required to model details of the optical bench, which accommodates a variety of critical elements, a coarser grid could be used for the spacecraft surface and the shields. To include external influences on the instrument into our model, we defined so-called ‘boundary nodes’ and set them to specific temperatures. For example, the ends of the struts attached to the spacecraft were set to 300 K, corresponding to the temperature of the spacecraft interior, and the void of space was modeled as a boundary node of 3 K. Similarly, we could assign dissipation values to individual nodes in order to model electrical and optical dissipation in CCD head and cavity mirrors, respectively.

To model radiative energy exchange, a geometric surface model of the instrument is created where nodes are represented by surface elements of area $A$, as visualized by the mesh delineating the instrument and bench models of figures 1 (right) and 2 (left), respectively. Each surface element has a specific emissivity $\epsilon$ and emits photons across its entire area, which is modeled as a gray-body segment, resulting in a heat flux $\phi$ according to Stefan’s law $\phi = \sigma A \epsilon T^4$. The net radiative energy exchange $\phi_{ij}$ between two surface elements $i, j$ is given by

$$\phi_{ij} = GR_{ij} \sigma (T_i^4 - T_j^4).$$  \hspace{1cm} (1)

The radiative coupling parameter $GR_{ij}$ between the two surface elements depends on the respective emissivities $\epsilon_i, \epsilon_j$ and on the view factor $F_{ij}$ between the two elements via the relation $GR_{ij} = \epsilon_i \epsilon_j A_i F_{ij}$, where $A_i$ is the area of surface element $i$. The view factor $F_{ij}$ is defined as the proportion of the total thermal flux emitted by element $i$ that is received by element $j$. It is determined from the geometric surface model of the instrument for each pair of surface elements through Monte Carlo simulations that simulate the emission according to Lambertian statistics and propagation between surface elements of electromagnetic rays.

The second important path of heat transfer is through conduction, which may be described by Fourier’s law for the heat flow $\dot{Q}$ through an interface area $A$ along the $x$-direction: $\dot{Q} = -\kappa A dT/dx$, where $\kappa$ is the thermal conductivity. In discretized form, the heat flow $\dot{Q}_{ij}$ between two nodes $i, j$, which are assumed to lie in the center of corresponding building blocks, may be written as

$$\dot{Q}_{ij} = GL_{ij} (T_i - T_j).$$  \hspace{1cm} (2)

The coupling parameter $GL_{ij}$ depends on the thermal conductivity $\kappa$ of the material, the interface area $A$ between the two nodal volume segments and the distance $d_{ij}$ between the nodes via the relation $GL_{ij} = \kappa A/d_{ij}$.

The full thermal model of the instrument comprises both surface and volume nodes, with the respective radiative and conductive coupling parameters. All conductive coupling parameters were manually inserted in the code and also used to describe the effects of components with no actual representation in the geometric model, such as the effect of the electrical harness. As the thermal conductivity changes with temperature, it is important to consider its variation over the full temperature range applicable to our analyses.
The corresponding data tables were obtained for the relevant materials, including aluminum, titanium, steel, glass-fiber reinforced plastic and Zerodur, from existing measurements for the Gaia and Herschel missions or from the manufacturer and manually included in the analyses [37].

3.1. Radiative energy exchange

In a first step, we aimed at optimizing the number and geometry of the radiation shields while heat conduction and dissipation were neglected. A graphical representation of the shields is shown in figure 3 (right), where the dotted line demonstrates that neither the optical bench nor any of its components are in direct field of view with any part of the spacecraft surface, thereby blocking any direct exchange of thermal photons. The main idea behind the geometric design is that the shields are fanned by successively increasing their opening angle \( \varphi \) to space. Through this method, the radiative coupling between the two outer shields and the cold void of space is improved with respect to a plane-parallel geometry. The coupling to space is further stimulated by covering the upper side of the shields with a highly emissive material (black finish), while impairing coupling in between shields by covering their underside with a low-emissivity material (gold finish). Care must be taken that the opening angle of the inner shield \( \varphi_3 \) is not too large as this would increase the radiative coupling to the optical bench with a corresponding increase of its temperature. Therefore, the optimum geometry must strike a fine balance between all these effects while also considering an adequate distance between spacecraft and shields.

For our analyses, the spacecraft surface was modeled with a circular shape of 1.4 m diameter (see blue area in figure 1 (right)) and the optical bench was kept at a fixed distance of 32.5 cm from that surface. This approach allows for a low-mass and compact shield design of a diameter only slightly larger than the structural cylinder of the spacecraft as shown in figure 1 (left). While, in principle, all three shield opening angles and distances to the spacecraft can be optimized, at first only the geometric parameters of the inner shield, \( \varphi_3 \) and \( d_3 \), were varied. The geometric parameters of the other shields were obtained via equipartition of the inner-shield parameters through the following relations: \( \varphi_1 = 1/3 \varphi_3 \), \( \varphi_2 = 2/3 \varphi_3 \) and \( d_1 = 1/2 d_3 \), \( d_2 = 3/4 d_3 \). Note that these constraints were confirmed to be close to optimal in subsequent analyses [37]. The results of the optimization are plotted in figure 4(a). The data show that the ideal opening angle \( \varphi_3 \) varies between 15° and 30° depending on the distance of the shield to the
Figure 4. (a) The optical-bench temperature is plotted against the opening angle of the inner shield $\phi_3$ for various distances to the spacecraft $d_3$. (b) The optical-bench temperature is plotted against the thermal coupling parameter between strut segments $G_{L_{st,st}}$ for various values of the coupling parameter between strut segments and radiation shields $G_{L_{st,rs}}$. (c) The optical-bench temperature is plotted against the value of electrical dissipation of the CCD head for various values of the electrical-harness cross-section $A$. The simulations included an optical dissipation of 0.2 mW. (d) The temperatures of the optical bench and test-volume are plotted against the size of the gold-coated top surface area of the optical bench. The gold-coated area is centered around the test volume and the coated area’s size is expressed as a percentage of the total top surface area.

spacecraft $d_3$. From this and similar analyses, an optimum temperature of $T_{\text{min}} = 8$ K is found for an opening angle $\phi_3 = 20^\circ$ at a distance of 20 cm. We also determined that, if only two shields are used instead of three, the minimum temperature rises to 15 K, which is a rather large increase and is deemed unacceptable. On the other hand, adding another solid metal shield only yields a small further reduction in temperature. The corresponding performance gain seems unjustified when traded against the higher cost and complexity. A simpler alternative is to add additional shield layers in the form of MLI sheets, which reduces the temperature of 2–3 K. This is discussed in the next section 3.2. For these reasons, we fix the design to a number of three shields and the geometric values specified above and proceed to the next step in the analysis.
3.2. Thermal conductivity

Heat conduction through any material that connects to the bench, including mechanical support struts, electrical wires and optical fibers, constitutes the biggest challenge in achieving cryogenic temperatures. For that purpose, we took utmost care to base the design on materials with low conductivity and to minimize the conduction across critical material-joints. Various ways of conductive heat transfer and the corresponding couplings are depicted in figure 3 (left).

Central to our design concept are the three mechanical struts. Each of them is composed from four segments of glass-fiber-reinforced polymer, which are hollow with a diameter of 15 mm and a wall thickness of 1 mm. The struts are joined by titanium end fittings at the penetration point of each shield. This allows obtaining low coupling parameters $GL_{st,st}$ between the strut segments. While it is essential to minimize the coupling between the strut segments to increase the thermal resistance of the heat flow, it turns out to be advantageous to maximize the coupling between the struts and the radiation shields, described by the parameter $GL_{st,rs}$. This can be explained by the cooling capacity of the shields, which remove heat from the struts and thereby successively reduce the amount of heat transported to the optical bench. This relationship becomes apparent from figure 3(b), where an optical-bench temperature of $T_{ob} \sim 27$ K is obtained for realistic coupling parameters around $0.05 \text{ W K}^{-1}$.

These results indicate the significance of solid metal shields for helping to cool the support struts in addition to their primary role as radiation shields. In our design, we assumed the shields to be made from aluminum of 1 mm thickness with applied surface coatings as described in the preceding section 3.1. In a renewed effort to improve the radiation shielding beyond the efficiency of the three-layer solid metal design adopted so far, three more layers were added as simple MLI sheets. These were affixed to the solid metal shields on top of spacers in the computer model, which yielded a further reduction in the optical-bench temperature of 2–3 K. Another coupling parameter, $GL_{st,ob}$, which describes the coupling between the struts and the optical bench, seemed to be less important for the optical-bench temperature. Reducing this parameter by two orders of magnitude only decreased the temperature by 1 K.

Aside from the mechanical-support struts, the second major medium for heat conduction is the electrical harness (made from low-conductive steel) which connects to the CCD head on the optical bench. As shown in figure 4(c), the effect on the optical bench temperature is only moderate as long as the wire cross section does not exceed 0.1 mm$^2$. The heat transfer through the optical fibers is relatively small and can be neglected in comparison to the electrical wires.

3.3. Dissipation

Dissipation is the final contribution to be included in the thermal analysis. The simulation results shown in figure 4(c) were performed with a detailed model of the optical bench (see figure 2). The model included 0.2 mW of optical dissipation in addition to the electrical dissipation of the CCD head for various harness cross-sections $A$. The plots demonstrate how the temperature rapidly increases once the electrical dissipation exceeds 1 mW. Fortunately, dissipation as low as 1 mW constitutes a realistic design goal, which can be achieved with a state-of-the-art CCD chip like the one used in the MIRI instrument of the JWST [38]. An additional electrical dissipation of 10 mW in a pre-processing chip, which was used in the design of all cryogenic JWST instruments [39], was included in our thermal analyses. We found it to be uncritical once we placed the chip below the outer shield, well within a reasonable distance of $<0.5$ m between chip and CCD head.
Figure 5. The temperature of the gold-coated optical bench including all radiative, conductive and dissipative effects. The dissipation of the CCD head (1 mW) and of the cavity mirrors (<0.2 mW) affects an increase in temperature of the respective components.

3.4. Summary and credibility of thermal analyses

It shall be noted that there are sometimes pronounced differences between the results of thermal analyses before launch and the actual measurements in orbit. The discrepancies are often due to the uncertainties in conductive couplings between material joints and other parameters. To mitigate these sources of error, we performed sensitivity analyses for relevant parameters in our model as we described in the preceding sections. These parameters were varied over a large range of values, as summarized in figure 3. The results indicate which parameter value ranges are acceptable to achieve the desirable temperature of 27 K for the optical bench. As an example, although the exact conductive coupling parameter between strut segments is not known precisely, we note that even a conservative value of $K_{St-St} = 0.05 \text{ W K}^{-1}$ allows achieving the target temperature. Likewise, power dissipation and harness cross-section must not exceed 1 mW and 0.1 mm$^2$, respectively, to obtain the target temperature. These parameters are realistic and shown to be attainable by comparison to equipment from other missions.

In summary, after choosing realistic values for thermal conductivity and electrical dissipation, we obtain an optical-bench temperature of ~27 K. This defines a limit we may achieve in an optimized design for radiation shields and mechanical structures without using active cooling. Figure 5 shows the temperature of the thermal nodes defining the optical bench, where the bench surface was modeled with an applied gold coating (see section 4.1). Due to the good thermal conductivity of the optical bench, the temperature varies only slightly across the bench. The temperature peaks at the CCD head and at the two cavity mirrors, where most of the electrical and optical power is dissipated, respectively.

4. The experiment

4.1. Driving factors

So far, we have aimed to optimize the experimental design with respect to the temperature of the optical bench. However, what really counts in the experiment (from a thermal perspective)
is the effective temperature of the test volume located above the bench where the macroscopic quantum superposition evolves in free fall.

The temperature of the test volume is determined by the photon flux received by it and can be reduced by decreasing the photon emission into the volume. This can be achieved by coating the surface of the optical bench beneath the test volume with a material of low emissivity, such as gold. Figure 4(d) shows the simulation results for optical bench and test-volume temperatures when the area of surface coating is increased from 0 to 100%. While this leads to only a moderate increase in the optical bench temperature due to the reduced coupling to space, the temperature of the test volume is dramatically decreased from 18 to 8 K. These results clearly demonstrate the benefits of a low-emissivity surface coating for reducing the photon flux, which by far outweighs the reduced cooling efficiency. For this reason, the optical bench is chosen to have a low-emissivity gold coating in the final design.

Note that, to facilitate the simulations underlying the data shown in figure 4(d), all the components of the optical bench as well as the electrical harness were removed, leaving a plain bench surface without any protruding elements. After placing these components back onto the gold-coated optical bench, another thermal analysis was performed to yield the results for the final configuration. It was somewhat surprising to find that the temperature of the experimental volume jumped from roughly 8 K for the naked bench to 16 K for the populated one. After repeating the process of re-populating the bench, this time adding one component after the other and performing a thermal analysis after each step, we found that a single critical item is responsible for almost the full rise in temperature: the collecting lens of the imaging system. Whereas other optical components, like the cavity mirrors, are quite far from the test volume and covered by a gold coating to minimize thermal emission, the uncoated imaging lens is in close proximity to the test volume and highly emissive. Consequently, the photon emission from the imaging lens constitutes the limiting factor for the temperature of the test volume. That temperature was found to be 16.4 K after taking into account all conductive and dissipative effects and the final material properties for emissivity and thermal coupling. The temperature of the test volume may be reduced some more if the lens is placed further away from it or the lens diameter is decreased. However, this comes at the expense of a reduced numerical aperture of the imaging system. Therefore, the benefit of even lower temperatures must be carefully balanced against the penalty of reduced resolution in any modification of the bench design. If the lens is removed, this reduces the temperature of the test volume to approximately 12 K, which gives an indication of the possible improvement for an optimized optical setup.

4.2. Simulated experimental results

Now that the instrument design has been optimized to obtain the lowest-possible temperatures in the experimental volume above the optical bench, we shall investigate the corresponding implications for the experimental measurements. In particular, we will consider the implications for distinguishing the predictions of quantum theory and the predictions of various macrorealistic models. As discussed in the introduction, keeping the temperature of the experimental volume as well as the internal temperature of the nanosphere very low, is a key requirement for a successful experiment. Other essential requirements, such as very low background pressure, very low levels of acceleration noise and very long free-fall times, have already been shown to be attainable in space [31]. In fact, these requirements present the primary motivation for going into space because such experimental conditions cannot be achieved on the
Figure 6. The expected interference visibility is plotted against environmental (left) and internal (right) temperature of the nanosphere, assuming an environmental temperature of 16.4 K for the right plot. The solid lines correspond to the predictions of quantum theory, the dashed lines represent the predictions of the macrorealistic model of Károlyházy. Its prediction is zero apart from small numerical uncertainties in the numerical simulation. All other macrorealistic models predict zero visibility for the given parameter regime. Therefore, a test of all models is possible for a temperature where the quantum-theoretical prediction for the visibility exceeds the highest prediction of all alternative models (shaded region).

ground. Our proposal for a passively cooled instrument without using liquid helium also avoids contamination of the experimental volume with helium molecules. These are highly diffusive and present a serious problem: any collision of a helium molecule with the nanosphere would lead to a localization of the quantum state and must be avoided by all means.

The technical requirements of MAQRO are chosen such that they allow, in principle, to test most macrorealistic extensions of quantum theory known today. In particular, if we observe a non-zero interference visibility for nanospheres with a mass of $\sim 10^{10}$ amu, this would already rule out the quantum-gravity model of Ellis et al [7], and it would largely rule out the CSL model—at least over a vast parameter regime including the original parameters proposed in [4, 5]. Moreover, MAQRO would allow for testing the models of Diósi [1] and Penrose [2], and it may even allow for testing the model of Károlyházy [3]. Of course, this depends on how well we can isolate our quantum system from the environment. In order to test macrorealistic extensions of quantum theory, quantum theory itself has to predict a non-vanishing interference visibility. If we assume that the vacuum is good enough ($\lesssim 10^{-13}$ Pa) to allow for neglecting decoherence due to gas scattering, the main decoherence mechanisms remaining are the scattering, absorption and the emission of black-body radiation. In the present paper, we are concerned with the environment temperature, i.e. with decoherence due to scattering and absorption of black-body radiation. In figure 6 (left), we show the dependence of the interference visibility on the environment temperature. The figure shows predictions of quantum theory (solid lines) for a nanoparticle with a radius of 90 nm and a mass density of 5510 kg m$^{-3}$ (Schott glass SF57HT). The dashed lines in the figure represent the predictions of the Károlyházy model, and the shaded regions indicate where quantum theory predicts a higher interference visibility than the macrorealistic model. Note that the interference visibility predicted by the CSL model, the Diósi–Penrose model and the quantum-gravity model of Ellis is zero in all these plots. An observation of a non-zero interference visibility would, therefore, rule out all these models.
MAQRO will aim to measure the dependence of the interference visibility on various parameters like particle size and mass density in order to allow for a quantitative characterization of the decoherence mechanisms involved.

To keep the functional dependence in figure 6 (left) simple, we assume that the internal temperature of the nanosphere is equal to the environment temperature. Of course, that is an idealized assumption because the nanoparticle will heat up while it is optically trapped. We show the functional dependence of the interference visibility on the nanoparticle’s temperature in figure 6 (right). Here, we assumed an environment temperature of 16.4 K, which is the result predicted by our thermal analysis for the spherical test volume shown in figure 4. Note that our simulations predicting the interference visibility assumed an isotropic distribution of the black-body photons scattered and absorbed. Due to the shield geometry developed here it may be necessary to take into account an anisotropic distribution of the black-body radiation. This will be investigated in the future.

5. Conclusion

Due to the inherent difficulties in combining the fundamental concepts of quantum theory and Einstein’s theory of general relativity, it is often believed that the basic formulation of either theory may prove to be incomplete. Therefore, theoretical predictions are expected to deviate from sufficiently accurate measurements. Such deviations can be investigated in various ways: on the one hand, Einstein’s equivalence principle as the foundation of general relativity can be put to the test. This has been done in numerous ground-based experiments and is proposed to be attempted at even higher accuracy for the future space missions ACES [40], MICROSCOPE [41], STEP [42] and STE-QUEST [43]. On the other hand, the superposition principle as a central concept of quantum theory could be tested by addressing the question, whether quantum mechanics as we know it still holds for increasingly massive objects. Such an experiment is at the core of the proposed MAQRO mission [17].

MAQRO addresses the question whether experiments to observe quantum superpositions of macroscopic objects could be successfully performed in space. In order to test the coherence properties of such states against the currently proposed modifications of quantum theory, including those motivated by quantum gravity, it is essential to minimize the ‘natural’ decoherence due to coupling with the environment that follows from conventional quantum mechanics. To perform such measurements, the quantum state must evolve freely for long periods of time in a cryogenic environment where black-body photon emission and scattering are suppressed to a high degree.

For this purpose, a cryogenic instrument design based on passive cooling through radiative coupling to the cold void of space was developed. The concept does not employ cryogenic coolants, which not only make it cheaper and less complex but also avoids diffusive contamination. Optimal radiative shielding from the hot spacecraft surface, minimal conductive coupling to the spacecraft interior as well as an appropriate choice and placement of dissipative components are key requirements to achieve the lowest possible temperatures. We obtained a temperature of approximately 27 K for the optical bench and a temperature of 16 K for the test volume where experiments are performed. The latter value is limited by the imaging lens and can be improved by reducing the numerical aperture. We then showed that—provided certain material properties are met for the test body—the achievable temperatures allow testing the decoherence rates predicted by all major macrorealistic models, which seems intractable in
ground-based experiments. Whilst the discussions in this paper focused on a specific type of experiment, the general design can be applied to other science experiments in space which aim for cryogenic temperatures of a compact optomechanical setup.

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References

[1] Diosi L 1984 Gravitation and quantum-mechanical localization of macro-objects Phys. Lett. A 105 199–202
[2] Penrose R 1996 On gravity’s role in quantum state reduction Gen. Rel. Grav. 28 581–600
[3] Karolyhazy F 1966 Gravitation and quantum mechanics of macroscopic objects Nuovo Cimento A 42 390–402
[4] Pearle P 1976 Reduction of the state vector by a nonlinear Schrödinger equation Phys. Rev. D 13 857
[5] Ghirardi G C, Rimini A and Weber T 1986 Unified dynamics for microscopic and macroscopic systems Phys. Rev. D 34 470
[6] Gisin N 1989 Stochastic quantum dynamics and relativity Helv. Phys. Acta 62 363
[7] Ellis J, Hagelin J S, Nanopoulos D V and Srednicki M 1984 Search for violations of quantum mechanics Nucl. Phys. B 241 381–405
[8] Romero-Isart O 2011 Quantum superposition of massive objects and collapse models Phys. Rev. A 84 052121
[9] Bassi A, Lochan K, Satin S, Singh T P and Ulbricht H 2013 Models of wave-function collapse, underlying theories and experimental tests Rev. Mod. Phys. 85 471
[10] Brune M, Hagley E, Dreyer J, Maitre X, Maali A, Wunderlich C, Raimond J M and Haroche S 1996 Observing the progressive decoherence of the ‘meter’ in a quantum measurement Phys. Rev. Lett. 77 4887
[11] Fickler R, Lapkiewicz R, Plick W N, Krenn M, Schaeff C, Ramelow S and Zeilinger A 2012 Quantum entanglement of high angular momenta Nature 406 43–6
[12] Friedman J R, Patel V, Chen W, Tolpygo S K and Lukens J E 2000 Quantum superposition of distinct macroscopic states Nature 406 43–6
[13] van der Wal C H 2000 Quantum superposition of macroscopic persistent-current states Science 290 773–7
[14] Jylsgaard B, Kozhekin A and Polzik E S 2001 Experimental long-lived entanglement of two macroscopic objects Nature 413 400–3
[15] Arndt M, Nairz O, Vos-Andreae J, Keller C, Van der Zouw G and Zeilinger A 1999 Wave–particle duality of C60 molecules Nature 401 680–2
[16] Gerlich S, Eibenberger S, Tomandl M, Nimmrichter S, Hornberger K, Fagan P J, Tüxen J, Mayor M and Arndt M 2011 Quantum interference of large organic molecules Nature Commun. 2 263
[17] Kaltenbaek R, Hechenblaikner G, Kiesel N, Romero-Isart O, Schwab K C, Johann U and Aspelmeyer M 2012 Macroscopic quantum resonators (MAQRO) Exp. Astron. 34 123–64
[18] Davies J K, Hawarden T G and Mountain C M 1991 Radiatively cooled telescopes: a new direction for infrared space astronomy Acta Astronaut. 25 223–8
[19] Hawarden T G, Crane R, Thronson H A, Penny A J, Orlowska A H and Bradshaw T W 1995 Radiative and hybrid cooling of infrared space telescopes Space Sci. Rev. 74 45–56

[20] Smith R C and Patrick McCray W 2009 Beyond the Hubble space telescope: early development of the next generation space telescope Astrophysics in the Next Decade (Berlin: Springer) pp 31–51

[21] Everitt C W F et al 2011 Gravity probe B: final results of a space experiment to test general relativity Phys. Rev. Lett. 106 221101

[22] Göran Pilbratt L 2008 Herschel mission overview and key programmes Proc. SPIE 7010 701002–1

[23] Lightsey P A, Atkinson C, Clampin M and Feinberg L D 2012 James Webb space telescope: large deployable cryogenic telescope in space Opt. Eng. 51 011003

[24] Hechler M, Cobos J and d’Aiguablava P 2002 Herschel, Planck and Gaia orbit design Int. Conf. on Libration Point Orbits and Applications pp 115–35

[25] McNamara P et al 2008 Lisa Pathfinder Class. Quantum Grav. 25 114034

[26] Horak P, Hechenblaikner G, Klaus M, Gheri K M, Stecher H and Ritsch H 1997 Cavity-induced atom cooling in the strong coupling regime Phys. Rev. Lett. 79 4974–7

[27] Barker P F 2010 Doppler cooling a microsphere Phys. Rev. Lett. 105 073002

[28] Kiesel N, Blaser F, Delic U, Grass D, Kaltenbaek R and Aspelmeyer M 2013 Cavity cooling of an optically levitated nanoparticle Proc. Nat. Acad. Sci. USA 110 14180–5

[29] Gieseler J, Deutsch B, Quidant R and Novotny L 2012 Subkelvin parametric feedback cooling of a laser-trapped nanoparticle Phys. Rev. Lett. 109 103603

[30] Li T, Kheifets S and Raizen M G 2011 Millikelvin cooling of an optically trapped microsphere in vacuum Nature Phys. 7 527–30

[31] Kaltenbaek R 2013 Testing quantum physics in space using optically trapped nanospheres Proc. SPIE 8810 88100B

[32] Romero-Isart O, Pflanzer A C, Blaser F, Kaltenbaek R, Kiesel N, Aspelmeyer M and Cirac J I 2011 Large quantum superpositions and interference of massive nanometer-sized objects Phys. Rev. Lett. 107 020405

[33] Honnen K, Kommer A, Messerschmidt B and Wiehe T 2008 NIRSpec OA development process of SiC components Proc. SPIE 7018 70180R-13

[34] Bougoin M and Lavenac J 2011 From Herschel to Gaia: 3 meter class SiC space optics Proc. SPIE 8126 81260V

[35] Elliffe E J, Bogenstahl J, Deshpande A, Hough J, Killow C, Reid S, Robertson D, Rowan S, Ward H and Cagnoli G 2005 Hydroxide-catalysis bonding for stable optical systems for space Class. Quantum Grav. 22 S257

[36] Engines UK and ITP Ltd 2010 Thermal ESATAN-TMS engineering manual Technical Report www.esatan-tms.com

[37] Hufgard F 2013 Thermal shield design for mission ‘Macroscopic Quantum Oscillators in Space’ Bachelor Thesis University of Stuttgart/EADS Astrium

[38] Love P J, Hoffman A W, Lum N A, Ando K J, Ritchie W D, Therrien N J, Toth A G and Holcombe R S 2004 1 K × 1 K Si:As IBC detector arrays for JWST MIRI and other applications Proc. SPIE 5499 86–96

[39] Loose M, Beletic J, Blackwell J, Garnett J, Wong S, Hall D, Jacobson S, Rieke M and Winters G 2005 The SIDECAR ASIC: focal plane electronics on a single chip Proc. SPIE 5904 59040V

[40] Salomon Ch et al 2001 Cold atoms in space and atomic clocks: ACES C. R. Acad. Sci. Ser. IV Phys. 2 1313–30

[41] Touboul P, Rodrigues M, Métris G and Tatry B 2001 MICROSCOPE, testing the equivalence principle in space C. R. Acad. Sci. Ser. IV Phys. 2 1271–86

[42] Sumner T J et al 2007 STEP (satellite test of the equivalence principle) Adv. Space Res. 39 254–8

[43] Schiller S et al 2010 Space time explorer and quantum equivalence principle space test (STE-QUEST): proposal in response to ESA M3 call 2010 for the Cosmic Vision programme Technical Report University of Düsseldorf (www.exphy.uni-duesseldorf.de/Publikationen/2010/STE-QUEST_final.pdf)