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The lead zeppelin : a force sensor without a handle

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Chapter 1

Introduction

The PhD dissertation that you are holding, describes the work that has been done over the last 4 years on a project called the Lead Zeppelin. Lead, a superconducting metal, is the material of choice in the measurements that have been performed. These involve the Zeppelin-part of the name: making a small piece of Lead float by means of magnetic levitation.

The inspiration for doing the Lead Zeppelin experiment came, in our case, from the Magnetic Resonance Force Microscopy (MRFM) community. In MRFM, a micrometer-sized ferromagnet attached to the end of a very soft cantilever is used to measure the tiny magnetic force between it and (nuclear) spins in a sample of interest. Much like MRI in hospitals, but on a much smaller scale: a striking result has been the measurement of the magnetic interaction between the ferromagnet and as few as ~ 500 nuclear spins[1]. One of the main goals of these experiments is to image complex molecules (like proteins or viruses) in their natural environment, in 3D and with atomic resolution.

The key to doing such sensitive experiments, is to obtain as low a force noise on the force sensor as possible. A low force noise requires, among other things, a low damping. State-of-the-art MRFM has shown a damping coefficient of $\gamma \sim 10^{-15} \frac{\text{N}}{\text{m/s}}$, and a force noise of $2 \times 10^{-18} \frac{\text{N}}{\sqrt{\text{Hz}}}$ [2].

When thermally limited, the force noise is $\sqrt{4k_B T \gamma}$ as stated by the fluctuation-dissipation theorem[3]. To lower the force noise, then, one has two options. One can decrease the temperature: indeed, a force noise of $0.8 \times 10^{-18} \frac{\text{N}}{\sqrt{\text{Hz}}}$ has been documented by using a force sensor with a higher damping of $\gamma \sim 10^{-13} \frac{\text{N}}{\text{m/s}}$ at a low temperature of 28 mK[4]. Or, one can push γ way down: for instance in [5] an optically levitated glass nanosphere with a damping of $\gamma \sim 10^{-20} \frac{\text{N}}{\text{m/s}}$ has been reported with a force noise $S_F^{1/2} = 2 \times 10^{-20} \frac{\text{N}}{\sqrt{\text{Hz}}}$ at room temperature.

In principal, the main source of damping in MRFM experiments comes from clamping losses. Therefore, to get to an even lower γ it makes sense to get rid of the cantilever; without clamping losses the damping could plummet to unprecedented levels, and the force noise along with it. The Lead Zeppelin aims

to do just that: instead of a cantilever with a small ferromagnet attached to its end, we instead magnetically levitate a small superconductor.

Another important motivation to do the Lead Zeppelin experiment is the investigation of the quantum mechanical behaviour of heavy objects. Namely, it is evident that quantum mechanics breaks down for big objects like chairs and cats[6] and cups of coffee, while it is known to be an excellent theory to describe small objects like quarks and electrons. The superposition principle in quantum mechanics, or, as it is phrased in popular media, ‘being in two places at the same time’, is something that electrons do constantly, yet we never observe this for the large objects we encounter in everyday life. Somewhere along the way from small to big, *something* goes awry[7–9].

While at present it is not known for sure what exactly is responsible, a very likely candidate is gravity. Indeed, the time-coordinate, which is needed to describe the time-evolution of quantum states through the Schrödinger equation, becomes ill-defined when we put a heavy object in a superposition of positions: the curvature of spacetime by the presence of mass, which is what gravity is[10], is different depending on the position of the heavy object. So if it is in some fancy quantum superposition of positions, the notion of time-evolution breaks down[11–13]. It is therefore argued that the amount of mass of an object plays a pivotal role in the destruction of unitarity in quantum mechanics. If gravity has anything to do with it, there will be a mass-dependent time-scale in which the collapse of the wavefunction occurs[14]. Also, if gravity is the culprit, then a heavy quantum state will decohere even without the act of a measurement. Simultaneously it explains the measurement problem of ‘ordinary’ quantum states, in realizing that a measurement apparatus involves adding a (large) mass to the situation.

A theory of Quantum Gravity is yet to be written down, so we turn to experiments to guide the way. In a variety of realizations, the goal to do quantum mechanics with heavy objects is pursued[5, 15–23].

In the case of the Lead Zeppelin, we want it first and foremost to be a very sensitive force sensor. If we are sensitive enough to detect tiny gravitational forces, which is in itself a very cool thing to be able to do, we can start thinking about doing quantum measurements, which requires freezing out thermal phonons. As we will see in the rest of this dissertation, the sensitivity to tiny forces comes at the prize that unwanted forces must be kept from intruding into the experiment. In particular vibrations must be kept to a very low level, as they will set the Lead Zeppelin in motion very easily.

The outline of this thesis is as follows. In chapter 2 we will give an overview of the design considerations of the Lead Zeppelin experiment, that are necessary to do a successful measurement. One such design feature that proved important is the Persistent Current Switch (PCS) with which we decouple external noise sources from reaching the experiment to a great extent. We describe our PCS in chapter 3. When all considerations of chapter 2 were implemented, several experiments

were performed, which we present in chapter 4. Finally, in chapter 5 we discuss what can (or should) still be improved, and some of the ideas that we had whilst doing the experiments, that will make our desired future measurements more and more feasible.

