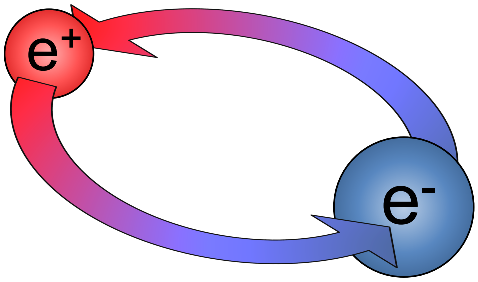
Large Momentum Transfer Interferometer
for Measuring the Gravitational Effect on Antimatter

INFN, Sezione di Firenze

Thesis Supervisor – Guglielmo Maria Tino, guglielmo.tino@unifi.it

Collaborations – Laboratorio Europeo di Spettroscopia non Lineare (LENS), Firenze
Università di Firenze (UniFi)
Università di Milano (UniMi)
Politecnico di Milano (PoliMi)

Motivation

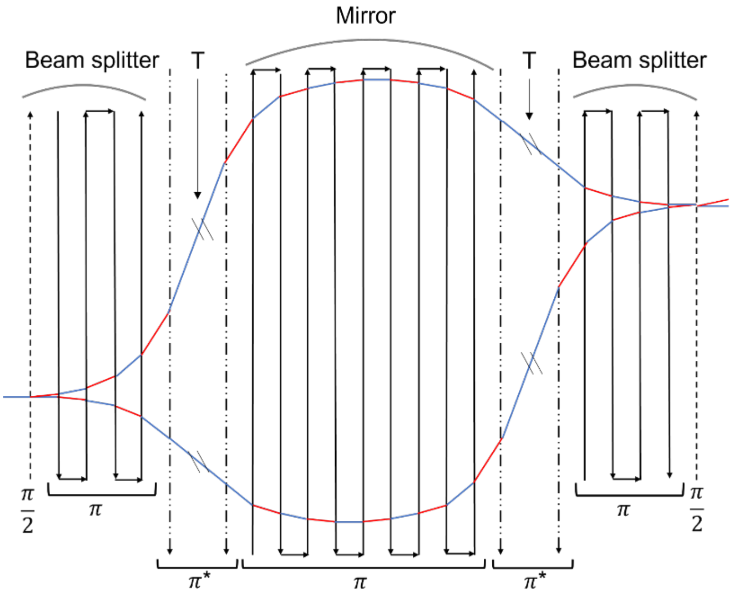


Positronium: the positron-electron (matter-antimatter) bound state

One of the most important present challenges in physics is to understand the nature of gravitational force and connect it with quantum mechanics. For a long time the Higgs boson has been considered the last missing piece of the standard model, the framework that describes the fundamental particles that build our universe. However, after its discovery, many questions remained unanswered and exotic particles such as those belonging to antimatter continue to be the subject of in-depth studies.
The thesis activity, which is well placed in the physical frame just described, is part of the INFN QUPLAS project (Quantum interferometry and gravitation with Positrons and LASers) which aims to measure the gravitational fall of a positron atom (Ps). As the simplest purely leptonic electromagnetically bound state, the Ps is known to be very well described by the ground state QED and represents a perfect probe since any variations from the theoretical model are attributable to the new physics. Antimatter gravitation has never been measured with a good ratio between gravitational and inertial mass; addressing this issue with Ps would have the advantage of studying a system whose total mass is the sum of the fundamental leptonic masses of the constituents, representing a test of the Einstein Equivalence Principle, the CPT symmetry and the antimatter antigravity theory. Moreover, there is a big lack of information about antimatter behaviour in a gravitational field.
Ps is quasi-stable: the singlet ground state (para-Ps) annihilates in 125 ps while the triplet state (ortho-Ps) has a lifetime of about 142 ns. If the positron that composes the atom meets an electron from the surrounding matter it annihilates. These constraints imply that the atom must be kept in Ultra High Vacuum and that it is necessary to quickly conclude the experiment making it particularly challenging.

Methods and objectives

A very precise way to measure an inertial displacement is by means of an interferometer: an atom that passes through a Mach-Zehnder interferometer is represented by a quantum superposition of wave functions having a phase shift proportional to the gravitational acceleration sensed by the atom, $\Delta\varphi=k_{eff}aT^2$, where k_{eff} is the effective momentum transferred to the atom by the interferometer, a is a generic gravity acceleration and T is the propagation time of the atom through the interferometer. To maximize the signal ($\Delta\varphi$) one could maximize k_{eff} or T but due to the reduced lifetimes of Ps we must focus on the effective momentum and for this reason a Large Momentum Transfer interferometer has been designed. The interferometer, on which the PhD activity is focused, is designed to be composed by a series of 23 pulses, being a technological challenge. Moreover, interferometers for inertial sensing usually operate with ultra-cold atoms and applying this technique to fast atomic beams (about 200 eV) represents a technological innovation pioneering applied to antimatter. There are three kinds of pulses: π/2 which symmetrically split the wave function, π which induces the transition from ground to excited state or viceversa, and π* which acts as a π pulse on one arm of the interferometer and as a 2π pulse on the other one (doesn't change Ps state).



Scheme of the light Interferometer. The Ps beam entering the apparatus propagates according to a laser-driven Mach-Zehnder scheme, in order to acquire a phase induced by the gravitational field.

The main goals of this PhD thesis are:

-) Optimize a novel laser system for a high power (max ≈100 W) and traveling wave interferometer using the laser coherent combination technique. For this power, a fairly large amplifier chain will be required and it will be necessary to develop a feedback and control system that is technologically more advanced than to those presently available.

-) Build and optimize the interferometer using advanced beam shaping techniques as those required to shape a particular flat top beam. Given the high number of pulses, this stage will be particularly challenging and relevant to the state of the art.

-) After interfacing the interferometer with the Ps source in the L-NESS laboratory in Como, the signal must be acquired and analyzed to extract the gravitational information. If necessary, a second interferometer will be built alongside the first to control the laser phase noise.

The activity will be carried out at the INFN Section in Firenze in strong connection with Milano.