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EXECUTIVE SUMMARY OF THE THESIS

Positron interferometry: towards the study of microwave influence

TESI MAGISTRALE IN ENGINEERING PHYSICS – INGEGNERIA FISICA

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1. Introduction

Interference of matter-waves is at the heart of quantum physics and has been observed on objects of increasing complexity, from electrons to neutrons and molecules. An experiment of interference of an antimatter particle, the positron, was performed for the first time in 2019, inside the project called QUPLAS. This paved the way for other important experiment on antimatter; this could lead to the study of gravitational acceleration of an antimatter system. This work is part of the QUPLAS (*QUantum interferometry, decoherence and gravity with Positron, positronium and LASers*) project. It is a collaboration between different institutions [1]. The main goal of this project is the study of the interferometric and gravitational properties of antimatter. QUPLAS is divided into three phases:

- QUPLAS-0: observation of interference of positrons in a Talbot- Lau interferometer.
- QUPLAS-I: observation of interference of positronium (Ps), again in a Talbot-Lau configuration.
- QUPLAS-II: measurement of the gravitational acceleration g_{Ps} of Positronium atoms by means of a Mach-Zender interferometer.

Besides the three incremental steps, there are a lot of transitional experiments and goal to achieve. QUPLAS-0 is just the starting point and paves the way to other intermediate experiments; in the context of the antimatter waves interferometry, an evolution of this experiment is proposed, the so-called *Quantum revival experiment*, which involves the interaction of a system showing quantum properties with a particular external perturbation. For this reason, there will be an upgrade of the system concerning QUPLAS-0 [2].

2. Experimental setup

The experiment makes use of the variable energy positron beam facility of the L-NESS laboratory in Como (Politecnico di Milano). Positrons are emitted by the isotope ^{22}Na, through a β^+ decay. After the emission, they have a kinetic energy characterized by a continuum spectrum. Therefore, they are made to pass through a tungsten foil which acts as a moderator. The moderation process is based on the fact that many solids have a negative positron work function; in this work, tungsten is picked as the material with negative work function, which is around -3 eV [3]. One problem that can alter the feasibility of the moderation process is the fact that positrons can be trapped in defects during the diffusion. Therefore the moderator was prepared by a thermal treatment; this consisted in a series of cycles in which the temperature is increased by steps, followed by a very low cool down. Four cycles has been performed, following the parameters of Table 1. The process of thermal annealing resulted essential to improve the number of positrons necessary for the interferometric experiment.

Step #	Approximate T (°C) (±60°C)	Bombardment duration (s)
1	840	1800
2	1100	1800
3	1300	600
4	1600	100
5	1850	100
6	2100	10

Table 1: W-conditioning parameters employed.

The fraction of positrons moderated by the tungsten foil must be separated from all the other positrons emitted at high kinetic energy. For this reason, there is the need of a guiding system, constituted by electrostatic optics. The system is formed by two perpendicular arms, forming a L, with a series of tubes placed at certain potentials. The goal is to guide the beam and accelerate it at 14 keV, which is the condition of maximum contrast for the interference pattern.

2.1. Interferometer

To perform an experiment of interferometry with positrons a particular configuration of the interferometer should be adopted. In this work, an asymmetric Talbot-Lau configuration [4] is used. It consists in a magnifying setup for the direct detection of the interference fringes with nuclear emulsion detector. This configuration has an important advantage: it allows to exploit an incoherent particle beam to perform the experiment of interferometry.
Considering the five-six order of magnitude separating the typical transit time through the interferometer (10 ns) and the average time distance between consecutive positrons (1-10 ms) a single particle experiment is realized. In this regime any interaction between interfering particle can be neglected.

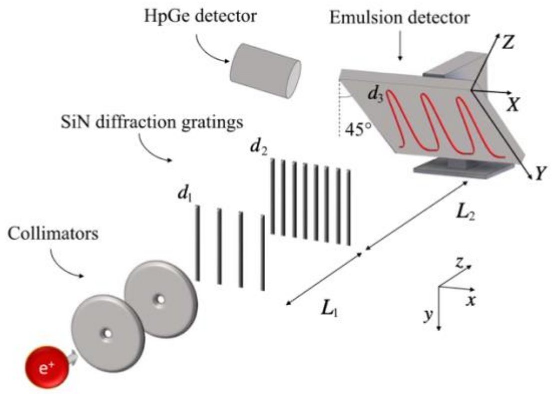

Figure 1: representation of the interferometer. Positrons traverse two circular 2-mm-wide collimators 10.2 cm apart. The interferometer is composed of two SiN diffraction gratings with periodicity $d_1 = 1.2\,\mu m$ and $d_2 = 1\,\mu m$, respectively, separated by $L1 = (118.6 \pm 0.2)$ mm. Interference fringes with $d_3 = 6\,\mu m$ periodicity are expected at $L2 \sim 580$ mm. The emulsion is tilted so that the Y axis in the reference frame of the emulsion surface (X, Y) forms a 45° angle with the y axis of the laboratory. Gamma rays (511 keV) from positron annihilation in the emulsion are monitored with a high-purity germanium (HpGe) detector for rate measurement.

During the mounting of the interferometer the rotational and longitudinal alignment of the two gratings was performed. Longitudinal alignment is about setting the right distances between the components of the interferometer. Rotational alignment is about putting the two gratings parallel. The approach adopted to align the gratings consisted in rotating the second grating, mounted on a piezoelectric rotator.

2.2. Microwave modulus

The novelty of this project, compared to the previous QUPLAS-0 interferometry experiment [2] consists in an additional phase term in the positron wavefunction. The additional perturbation consists in a 10 GHz microwave stationary field, generated inside a cavity. The positron-microwave interaction produces an effect related to the undulatory nature of positrons. The plan is to supplement the apparatus by a cavity, located after the second grating, in which a standing microwave field is generated. In a "classical" language the single positron crossing the second grating will interact with photons in the microwave field.

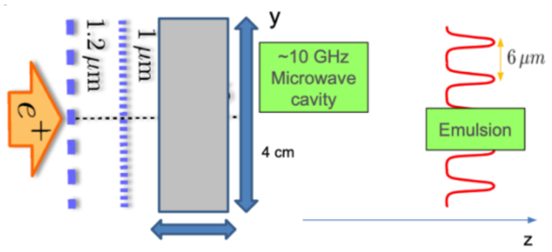

Figure 2: scheme of the apparatus with the cavity.

The cavity is a special type of resonator, consisting in a structure made of brass, which has a very-low-magnetic influence on the positron beam. The microwaves bounce back and forth between the wall of the cavity and at the cavity's resonant frequency they reenforce to form standing waves. The field is externally tunable by changing the microwave power. The power is selected using attenuators. Changing the attenuation, it is possible to repeat the experiment with different intensities of the electric field.

Figure 3: image of the microwave cavity.

The single positron crossing the second grating will interact with photons. The amplitude of the required field varies along the perpendicular plane according to the direction of propagation of the particle, so that the different paths that the particle takes at the same time, undergo a different phase shift. This should correspond to a variation of the interference pattern position on the detector. The shift of the fringes position will depend on the phase of the field when the antiparticle enters in the cavity; nevertheless, the phase of the positron at the entrance is completely random. Therefore, a reduction in the visibility of the interference pattern is expected. This effect is called decoherence.

Beyond this decoherence effect, it could be also expected a periodic variation of the visibility as increasing the electric field intensity. This effect is called *revival*. This consists in periodically losing and recovering the coherence (Figure 4).

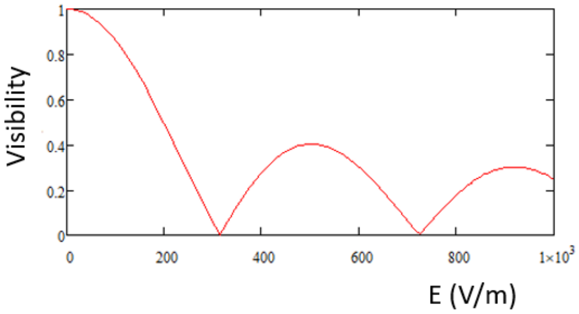

Figure 4: visibility as a function of the electric field in the theoretical model [5].

2.3. Emulsion detector

At the detector the periodicity of the fringes is expected to be around 6 μm. Therefore, a resolution better than 1 μm is required to resolve the periodicity. Nuclear emulsions have a sub-micrometric resolution, which makes them good options for positron interferometric studies [6]. Nuclear emulsions are composed by silver bromide microcrystals with a diameter of 0.04 μm, embedded in a gelatin matrix. The kinetic energy released by the positron is transferred to the silver bromide microcrystals, resulting in the creation of a silver grain in the order of 1 μm, visible through an optical microscope.

The new generation of nuclear emulsions are produced by the Giovanni De Lellis' group at the Gran Sasso Laboratory. After each exposure the emulsions are digitalized in this scanning facility.

In order to assess the performance of the emulsion to distinguish the periodicity of a pattern, an experimental test was performed. It consisted in placing a grating of periodicity of 7 μm in close contact with the emulsion surface (Figure 5). In this way it worked as a mask for the positrons, which came to the emulsion producing the periodic pattern of the grating. In other words, they projected the periodicity of the gratings on the emulsion.

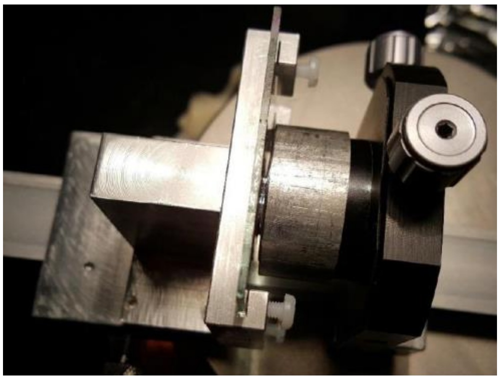

Figure 5: image of the grating putted (almost) in contact with the emulsion.

The kinetic energy of positron was fixed at 10keV. This energy was chosen to reduce the positron transmission with respect to the case of 14keV.
In all the cases the periodicity resulted clearly visible.

3. Characterization of the beam

One important aspect for the realization of the experiment is the characterization and consequent optimization of the positron beam. This was done thanks to the use of a microchannel plate (MCP), coupled to a phosphor screen. This system allowed a real-time characterization of the beam.
An important aspect is the optimization of the beam, which means the correction of the potentials applied to the optics in order to obtain a symmetric beam, suitable for the experiment.
The gratings have dimensions of 3 mm x 3 mm; as a consequence, the beam (treated as gaussian) should be in the order of 2 mm in term of full width at half maximum (FWHM) (at least at the position of the first grating).
After a first set of measurement the beam resulted to be asymmetric. In particular, it was elongated along the x-axis. This could have been due to a non-perfect bending of the beam at the electrostatic optics. The protocol adopted to improve the quality of the beam consisted in changing by few volts the values of some strategical tubes in the part of the electrostatic optics. After some operations, the conditions schematized in Table 2 were found.

V_F (kV)	$FWHM_x$ (mm)	$FWHM_y$ (mm)	number of positron (e^+/s)
9	1.78	1.60	$\sim 10^4$

Table 2: characteristics of the beam after some manipulations.

The next step was to mount the collimator. This was important to give the beam a better coherence. The effect of the collimator was to get a very small spot at the position of the first grating. Another effect, which is predictable, was that the number of positrons was diminished compared to before. This is obvious because the positrons outside 1 mm from the center of the collimator were removed from the beam. However, the number of positrons was still sufficient to conduct the experiment of interferometry.

V_F (kV)	$FWHM_x$ (mm)	$FWHM_y$ (mm)	number of positron (e^+/s)
9	1.22	0.90	$\sim 10^3$

Table 3: characteristics of the beam with the collimator.

Changing the focalization potential, the position at which the beam is focalized is changed. To have good statistics during the experiment, it is preferrable a great number of positrons at the emulsion detector. However, also a tiny spot (below 3 mm in diameter, which is the dimension of the gratings) is desirable; these two conditions are not always related, so there is the need of a trade-off. This is represented by the density of positrons per unit area. The best scenario is to focalize at the middle of the interferometer. In this way the beam is quite collimated throughout all the interferometer, in the sense that it doesn't diverge too much. The effect is that the density of positrons increases at the detector.

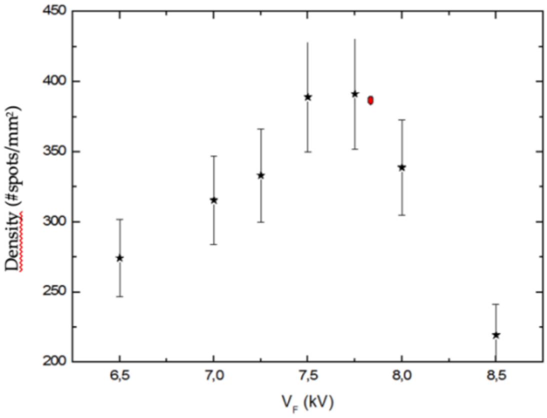

Figure 6: plot of the spot density for different focalization potentials.

Plotting the density of positrons per unit area (Figure 6), it is possible to observe that the better condition in term of density was around 7.5-7.8 kV. From the figure, the red dot was chosen as reference. This corresponds to 7.8 kV.

The number of positrons is a fundamental parameter to be considered. This impact the statistics and therefore the capability of observing an interference pattern at the detector. So, the number of positrons expected to reach the detector is used to estimate the time of exposure needed for conducting the experiment.

To summarize, at the beginning the number of positrons per second was $5 \cdot 10^3$, which became 10^3 after the collimator (~80% loss). Now, estimating that every grating "kills" half of the positrons (~90% loss) [3], the conclusion is that at the detector $\sim 2 \cdot 10^2$ positrons per second are expected.

To acquire sufficient statistics, there is the need of $3-4 \cdot 10^7$ grains in the analysis region [9]. Therefore, the time needed for a single exposure is around $2 \cdot 10^5$ seconds, which means around 2 days.

4. Preliminary results

A series of measurements were performed with the setup prepared and described previously. In particular, 3 measurements were performed with 3 different exposure times.

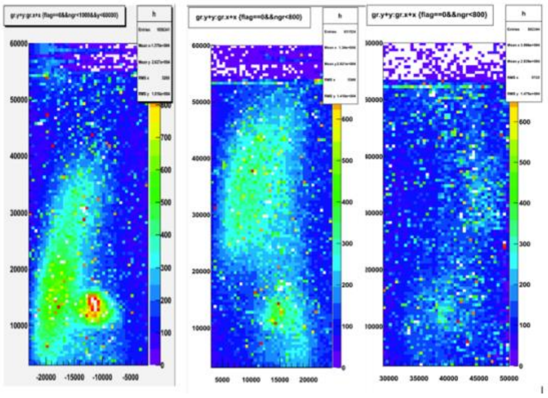

Figure 7: image of the signal on the various emulsions (time of exposure: 8h left, 24h middle, 64h right).

In all the measurements unexpected things happened. A second big signal, besides the right spot, appears as a coma. It is clearly visible in Figure 7. A lot of positrons "went" into the coma and so the statistic of the central spot was reduced. The periodicity results to be not clear in the central spot.

After a check of all the setup, it was possible to notice that the second grating was broken in the lower right corner. Therefore, many positrons came out of the hole creating the second signal.

The second grating was suddenly substituted and the interferometer was re-aligned before proceeding with a second series of measurements. For the second set of measurements the modulus of microwave was installed in the chamber. Moreover, the microwave field was kept off during the first measurement, in order to reproduce the interferometric experiment without any perturbation (looking for an improvement with respect to the first set of measurements). Then, in the two successive measurements the microwave field was turned on. Some critical values of the electric field were chosen, as shown in orange in Figure 8, in order to observe the revival predicted by theory.

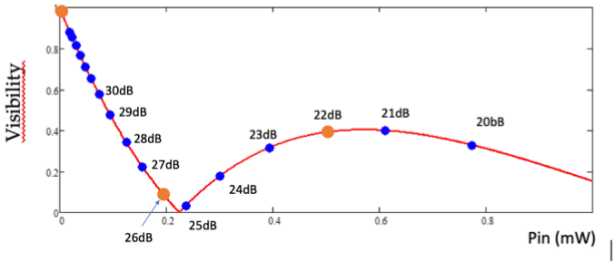

Figure 8: sketch of the three points (orange) of microwave field power chosen for the experiment.

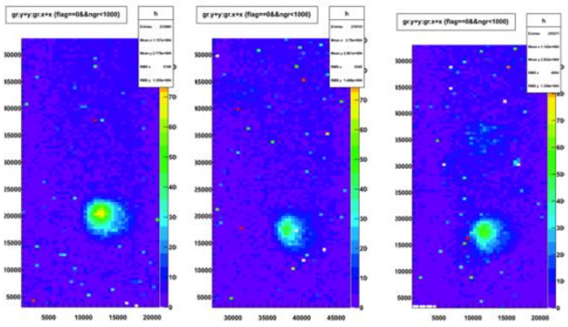

Figure 9: image of the signal on the three emulsions.

As reported in Figure 9, the signal on the emulsion is clearly visible and results in a single central spot (as expected). Therefore, an improvement with respect to the first set of measurements is evident.

From the analysis performed, in all the emulsions it results that the periodicity is still not visible. The results show that for a future campaign of measurement is necessary to increase the statistics and to improve the vacuum level. A pressure equal or smaller than 10^{-7} $mbar$ is desirable to conduct the experiment. Indeed, a bad vacuum means a higher probability of scattering between positrons and other particles. Scattering makes the particle-wave losing coherence [5].

5. Conclusions

During the thesis work a series of milestones have been achieved in order to carry out the *Quantum revival* experiment. Here are synthetized the main achievements:

- Thermal treatment of the moderator. This resulted important to improve the number of monochromatic positrons coming to the interferometer.
- Optimization of the transport condition of positron. This stage allowed improve the quality of the beam, optimizing the dimension of the spot and the number of positrons per second. The experimental setup has been improved with respect to the first QUPLAS-0 experiment.
- Periodicity test on the emulsions.
- Implementation of the interferometer. This consisted in mounting the interferometer, arranging the longitudinal and rotational alignment of the two gratings.
- First campaign of measurements. This step provided important information for future improvements of the setup and for future measurements.

In conclusion, the experiment is at an advanced stage for its implementation. Soon, the plan will be to improve the vacuum level and to increase the statistics of measurement.

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