The Observation of Antimatter Quantum Interference

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RÉSUMÉ. Selon le principe de dualité onde-particule, chaque particule massive possède une longueur d'onde liée à son impulsion par la constante de Planck. Ce concept révolutionnaire était l'une des fondements de la Physique Quantique et a été confirmé et directement observé pour plusieurs types de particules et d'objets quantiques. Je discuterai de l'observation récente de l'interférométrie quantique avec des positrons, qui confirme directement la dualité onde-particule pour l'Antimatière. Ceci a été réalisé en utilisant une configuration de faisceau d'une particule à la fois.

ABSTRACT. According to the principle of wave-particle duality, every massive particle has a wavelength related to its momentum by the Planck constant. This revolutionary concept was one of the cornerstones of Quantum Physics and has been confirmed and directly observed for several kind of particles and quantum objects. I will discuss the recent observation of quantum interferometry with positrons, which directly confirms the wave-particle duality for Antimatter. This result has been obtained in single-particle mode.

1 Introduction

The wave-particle duality hypothesis for massive particles was introduced by L. De Broglie in 1923 [1]. The momentum p of a particle is related to its wavelength by the Planck constant h, according to the famous relation $\lambda_{\mathrm{dB}} = h/p$, which together with the Uncertainty and the Superposition Principles constitutes one of the foundations of the Quantum Theory. This concept has now been tested in many different experimental conditions over the timespan of about a century.

The first experimental evidence of wave-like behavior of massive quantum particles was obtained with electrons in 1927 [2,3]. Neutrons then were demonstrated to display undulatory behavior in crystals [4], in the Earth gravitational field [5,6] and in double slit diffraction and interference experiments [7]. In 1995, interferometry were demonstrated for molecules [8] and a few years later for complex structures like fullerenes [9]. As a general statement, wavelike behavior of quantum objects has been studied in a variety of ways and has found several applications [10].

A special place among the various tests of the wavelike nature of quantum objects is held by interferometry of single particles, which, according to Feynman, constituted a test of the very essence of Quantum Physics [11]. These kind of experiments were pioneered by Merli, Missiroli and Pozzi who performed the first single-electron interference experiment in 1976 by using an electronic biprism [12], which is equivalent to the double-slit " gedanken experiment " configuration considered by Feynman. This experiment was then repeated by Tonomura and his group in 1989 [13] and performed with material gratings in 2012 [14].

No direct tests on wave properties of antiparticles were performed, with the exception of an indication of diffraction of positrons, obtained in 1980 [15].

2 Antimatter

The de Broglie hypothesis is one of the cornerstones of Quantum Mechanics – together with the Schrödinger equation, the Uncertainty Principle and the Born probabilistic interpretation of the wave function. They were followed, as a major logical next step, by the first quantum mechanical equation that was compatible with Special Relativity : the 1928 Dirac equation [16].

One of the consequences of the Dirac equation was the postulation of new states described by the formalism, which led in turn to the prediction and the subsequent discovery of the first antimatter particle in 1932: the positron [17]. Nowadays the existence of antimatter particles has been thoroughly established and is one of the characteristics of the Standard

Model of Particle Physics : every fundamental constituent (spin 1/2 fermion) has its own anti-fermion, with opposite charges and discrete quantum numbers.

The most general symmetry relating particles to antiparticles in the Standard Model is the CPT symmetry of Particle Physics, where C is the charge conjugation, P the parity inversion and T the time reversal operation. The combination of these discrete symmetries in the CPT operator constitutes one of the main symmetries of a lagrangian Lorentz-invariant gauge quantum theory. The CPT Theorem was formulated in 1957 [18] and predicts, among other things, the equality of masses and lifetimes of a particle and its antiparticle, as well as opposite discrete internal quantum numbers, like electric charge.

The importance of studying antimatter is related both to testing fundamental physical laws and to achieving a better understanding of the origin and composition of our Universe.

From the point of view of fundamental laws, antimatter systems offer the possibility of studying CPT invariance by searching for quantum gravity effects coming from the Planck scale that could potentially violate Lorentz invariance; this allows a series of tests of conservations laws, including the Einstein Equivalence Principle [19]. In modern quantum field theories CPT breaking is in fact closely related to Lorentz invariance violation by the Greenberg theorem [20].

Antimatter is also relevant to understanding the physical content (at least in terms of baryons and leptons) of our Universe and its asymmetry [21]. According the most widely accepted cosmological models, a chain of events occurring during the Electroweak Era (between 10^{-35} and 10^{-12} s of cosmic time) generated the small asymmetry that was critical to having a Universe only made of matter (and not antimatter). For this scenario to take place, the three Sakharov conditions need to be met, that include baryon number violation, departure from equilibrium and some level of CP violation [22]. The detailed mechanism for baryon and lepto-genesis – and its compatibility to the level of CP violation currently measured in the frame of the Standard Model is however still to be understood [23].

3 Antimatter Quantum Interferometry

While progress in understanding antimatter particles has been remarkable, no quantum interference experiment has been done with antimatter before 2018, mainly due to the scarcity of antiparticles produced in the form of a coherent beam. In addition, the specific form of interactions of antimatter requires special considerations both in the beam preparation as well as for the detection [24].

For the case of positrons, the subject of our study, we realized a setup consisting in the main conceptual elements of:

- A monochromatic beam obtained by means of a ^{22}Na source
- Diffraction from a set of SiN material gratings
- Detection of interference pattern by means of a high-resolution emulsion detector

The beam was obtained by moderation, acceleration and collimation of positrons coming from the source, obtaining a monochromatic beam of $\approx 10^4$ particles/s. Given this low flux, Talbot-Lau interferometry was selected as the technique of choice, motivated by the need to increase the acceptance as well as the possibility of obtaining a *magnifying* configuration, with the goal to detect an interferometric pattern with periodicity of several microns [25].

The validity of the proposed technique was studied first by assessing the sensitivity of the nuclear emulsions to low energy (10-20 keV) positrons [26]. Secondly, the capability of the emulsion to reconstruct a micrometric positron-generated interferometric pattern was tested, by masking the detector with a fine grating and exposing it to the e^+ beam [27].

The experiment was called QUPLAS-0, being the first stage of the QUPLAS (QUantum interferometry and gravitation with Positrons and LASers) program that makes use of quantum interferometry to study fundamental physical laws such as the CPT symmetry and the Einstein Equivalence Principle.

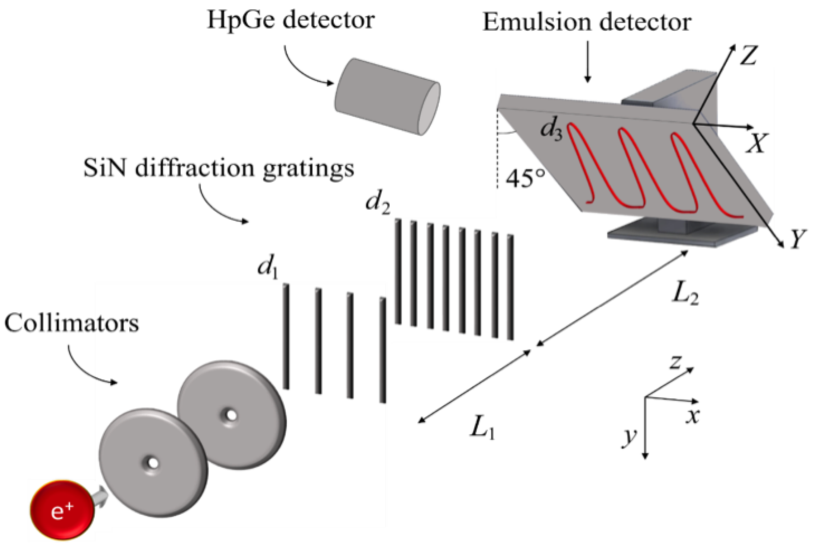

Fig. 1: Scheme of the QUPLAS-0 setup for e^+ interferometry. After a preliminary collimation stage, positrons propagate through a two gratings system with periodicities d_1 = 1.2 μm and d_2 = 1 μm respectively (open fraction of 50% in both cases). The distance L_1 is of 11.8 cm, while L_2 = 57.6 cm. This constitutes a magnifying Talbot-Lau configuration to form a signal of periodicity of 5.9 μm on the downstream emulsion detector, tilted by 45^0 to better cover the longitudinal region where the visibility of the Talbot-Lau peak is located, as discussed in the text. An HpGe detector is used as a beam monitor.

4 The Experiment

QUPLAS-0 is based on the beam generated by the ^{22}Na radioactive source at the Positron Laboratory of the Politecnico di Milano in Como. The electrostatic beamline system [28] guides the monochromatic positron beam (with kinetic energy tuneable in the 5-20 keV range) to the downstream interferometry setup schematized in fig. 1.

The Talbot-Lau interferometer is optimized for a positron kinetic energy of 14 keV, equivalent to a de Broglie wavelength of 10.3 pm ; it features a couple of carefully aligned SiN gratings having periodicities of 1.2 μm and 1 μm for the first and the second grating respectively. Their open fraction is of 50% and their relative distance L_1 is of 11.8 cm.

The centre of the emulsion detector is positioned at a distance of L_2 = 57.6 cm from the second grating. Under these conditions, the Talbot wavelength is given by $T_L = d_2{}^2/\lambda = 9.7$ cm and the magnification factor is given by $\eta = L_2/L_1 = 4.9$. The expected interferometric pattern at the position of the emulsion will have a periodicity $d_3 = \eta d_1 = 5.9\ \mu$m. The geometric configuration satisfies the Talbot-Lau resonance condition:

$$\frac{L_1}{L_2} = \frac{d_1}{d_2} - 1$$

The emulsion detector is positioned with a 45 degrees inclination centered at the resonance position in order to cover an extended longitudinal region: this is because the longitudinal (z-axis) position of the maxima in the Talbot-Lau carpet is affected by several possible geometrical errors and uncertainties and cannot be determined *a priori* with very high accuracy.

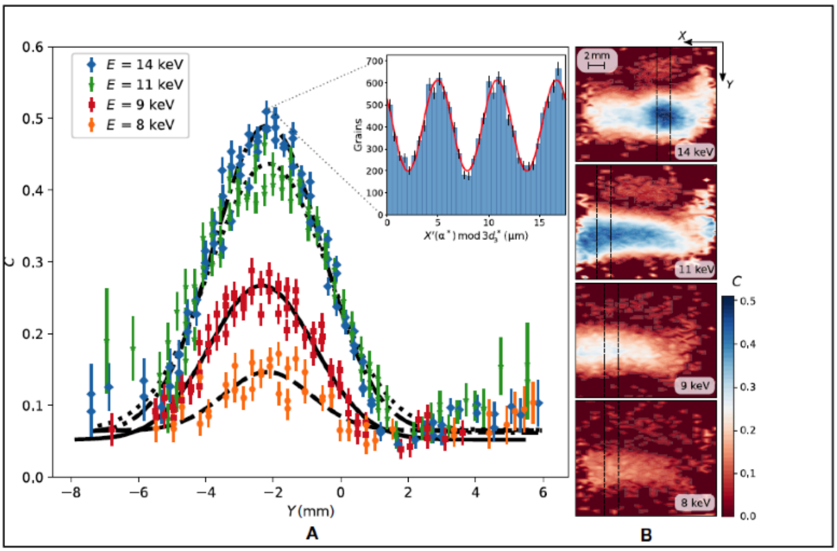

Fig. 2. The obtained contrast is plotted at a function of the longitudinal coordinate (left) for different energies of the positron beam. As expected, the highest contrast is obtained for the nominal resonance condition of 14 keV (see inset). The right hand side of the figure shows the contrast on the emulsion detector.

5 Results

The experimental measurements were made in the course of 2018, scanning over several available energies of the positron beam. The first step consisted in the identification of the interferometric pattern upon development of the emulsion detector, which works as an integrator of the interference pattern during the time of the data taking.

For different energies of the photon beam, the predicted undulatory pattern was observed with the expected wavelength of 5.9 μm, which is in agreement with the acceptance of the interferometric setup. The maximum visibility of the pattern was observed for the case of 14 keV kinetic-energy positrons as expected from the properties of their Talbot-Lau carpet.

A set of energies were studied, as shown in figure 2, from 8 to 14 keV, each showing a different contrast at the resonance condition ; this was already a clear indication of the quantum mechanical nature of the effect.

However, in order to fully demonstrate that the observed interferometric pattern was of quantum origin, a comparison was made with the deflectometric “ moiré ” regime, featuring a ballistic and completely classical and achromatic behavior [29]. A simulation was made of the quantum mechanical Talbot-Lau visibility pattern as a function of energy (or equivalently, of the de Broglie wavelength), to be compared with experimental data.

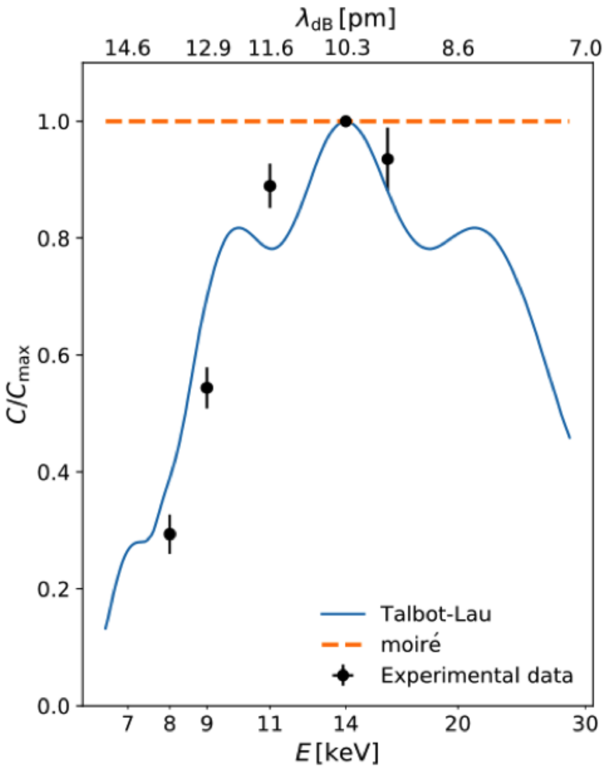

Fig. 3. Visibility contrast compared with the Talbot-Lau quantum mechanical prediction. The classical " moiré " ballistic behavior would give an achromatic result as a function of the de Broglie wavelength (the positron energy).

This visibility study is shown in fig. 3, where we have added another experimental point (not shown in fig. 2) at the energy of 16 keV for more completeness. The observed behavior is in agreement with the Talbot-Lau quantum mechanical interference model. We therefore conclude that we have unambiguously observed antimatter quantum interferometry [30].

Finally, it has to be stressed that our demonstration of antiparticle interference clearly pertains to the class of *single-particle* quantum experiments, based on the fact that the positron flow rate is of a modest $\approx 10^4$ particles per second at most, while the transit time through the

1 m long setup (fig. 1) is about 10^{-7} s. Moreover, the positron source is fully time-incoherent, being essentially driven by radioactive decays of uncorrelated ^{22}Na nuclei.

6 Conclusion

We have demonstrated quantum interferometry with antimatter, by using Talbot-Lau diffraction with positrons in single particle mode. This result is described in detail in [30].

References

[1] De Broglie L., *Nature* 112, 140 (1923).
[2] Davisson C.J., Germer L.H., *Proc. Natl. Acad. Sci. USA* 14, 317 (1928).
[3] Thomson G.P., Reid A., *Nature* 119, 890 (1927).
[4] Rauch H., Treimer W., Bonse U., *Phys. Lett. A*, 47, 369 (1974).
[5] Overhauser A.V., Colella R., *Phys. Rev. Lett.*, 33, 1237 (1974)
[6] Colella R., Overhauser A.V., Werner S.A., *Phys. Rev. Lett.*, 34, 1472 (1975).
[7] Zeilinger A. et al., *Rev. Mod. Phys.*, 60, 106 (1988).
[8] Chapman M.S. et al., *Phys. Rev. Lett.*, 74, 4783 (1995).
[9] Arndt M. et al., *Nature*, 401, 680 (1999).
[10] Tino G.M. and Kasevich M.A., *Atom Interferometry*, Proc. of the Int. School of Physics "Enrico Fermi", Varenna (Italy), vol. 188.
[11] Feynman R., *Feynman Lectures on Physics*, Feynman, Leighton, Sands. Ed. Addison-Wesley, Reading (MA), USA 1965 vol. 3.
[12] Merli P.G., Missiroli G.F., Pozzi G., *Am. J. Phys.*, 44, 306 (1976).
[13] Tonomura A. et al., *Am. J. Phys.*, 57, 117 (1989).
[14] Frabboni S. et al., *Ultramicroscopy*, 116, 73 (2012).
[15] Rosenberg I.J. et al., *Phys. Rev. Lett.*, 49, 1139 (1980).
[16] Dirac P.A.M., *Proc. R. Soc. Lond.*, A117, 610 (1928).
[17] Anderson C.D., *Science*, 76, 238 (1932).
[18] Lüders G., *Ann. Phys.*, 2, 1 (1957).
[19] Giammarchi M., G. Vinelli, *Universe*, 8, 123 (2022).
[20] Greenberg O.W., *Phys. Rev. Lett.*, 89, 231602 (2002).
[21] Dolgov A.P., *Surv. High En. Phys.*, 13, 83 (1998).
[22] Sakharov A.D., *J. Exp. Theory Phys. Lett.*, 5, 24 (1967).
[23] Dolgov A.P., *CP Violation in Cosmology*, Proc. of the Int. School of Physics "Enrico Fermi", Varenna (Italy), vol. 163. CP Violation: from Quark to Leptons.
[24] Sala S. et al., *J. Phys B*, 48, 195002 (2015).
[25] Sala S., Giammarchi M., Olivares S., *Phys. Rev. A*, 94, 033625 (2016).

[26] Aghion S. et al., *J. Instr. JINST*, 11, P06017 (2016).
[27] Aghion S. et al., *J. Instr. JINST*, 13, P05013 (2018).
[28] Ariga A. et al., *Nucl. Inst. & Meth. A*, 951, 163019 (2020).
[29] Giammarchi M., *Symmetry*, 11, 1247 (2019).
[30] Sala S. et al., *Sc. Adv.*, 5, eaav7610 (2019).