Experimental tests of Quantum Mechanics: from Pauli Exclusion Principle Violation to spontaneous collapse models

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Experimental tests of Quantum Mechanics: from Pauli Exclusion Principle Violation to spontaneous collapse models

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Abstract.
The Pauli exclusion principle (PEP) and, more generally, the spin-statistics connection, is at the very basis of our understanding of matter. The PEP spurs, presently, a lively debate on its possible limits, deeply rooted in the very foundations of Quantum Field Theory. Therefore, it is extremely important to test the limits of its validity. Quon theory provides a suitable mathematical framework of possible violation of PEP, where the q violation parameter translates into a probability of violating PEP. Experimentally, setting a bound on PEP violation means confining the q-parameter to a value very close to either 1 (for bosons) or -1 (for fermions). The VIP (Violation of the Pauli exclusion principle) experiment established a limit on the probability that PEP is violated by electrons, using the method of searching for PEP forbidden atomic transitions in copper. We describe the experimental method, the obtained results, both in terms of the q-parameter and as probability of PEP violation, we briefly discuss the results and present future plans to go beyond the actual limit by upgrading the experimental technique using vetoed new spectroscopic fast Silicon Drift Detectors. We mention as well the possibility of using a similar experimental technique to search for eventual X-rays generated as a signature of the spontaneous collapse of the wave function, predicted by continuous spontaneous localization type theories.

1. Introduction

The Pauli Exclusion Principle (PEP) plays a fundamental role in our understanding of many physical and chemical phenomena, from the periodic table of elements, to the electric conductivity in metals and to the degeneracy pressure (which makes white dwarfs and neutron stars stable). It is a consequence of the spin-statistics connection [1], and, as such, it is intimately connected to the basic axioms of quantum field theory [2]. Although the principle has been spectacularly confirmed by the number and accuracy of its predictions, its foundation lies deep in the structure of quantum theory and has defied all attempts to produce a simple proof, as nicely stressed by Feynman [3]. Given its basic standing in quantum theory, it is appropriate to carry out precise tests of the PEP validity and, indeed, mainly in the last 20 years, several experiments have been performed to search for possible small violations [4, 5, 6, 7, 8, 9, 10, 11, 12]. Often, these experiments were born as by-products of measurements with a different objective (e.g., dark matter searches, proton decay, etc.), and most of the recent limits on the validity of PEP have been obtained for nuclei or nucleons. Many (if not all) of these experiments are using methods which are not obeying the so-called Messiah-Greenberg superselection rule [13].

In 1988 Ramberg and Snow [14] performed a dedicated experiment, pioneering a technique avoiding the Messiah-Greenberg superselection rule by introducing new electrons in the system. They searched for anomalous X-ray transitions, that would point to a small violation of PEP in a copper conductor, circulating current into it. The result of the experiment was a probability [15] $\frac{\beta^2}{2}$<1.7×10^{-26} that the PEP is violated by electrons. The VIP Collaboration set up a much improved version of the Ramberg and Snow experiment, with a higher sensitivity apparatus [16]. Our final aim is to improve the PEP violation limit for electrons by 3-4 orders of magnitude, by using high resolution Charge-Coupled Devices (CCDs), as soft X-rays detectors [17, 18, 19, 20, 21], and decreasing the effect of background by a careful choice of the materials and sheltering the apparatus in the LNGS underground laboratory of the Italian Institute for Nuclear Physics (INFN).

In the next sections we describe the experimental setup and method, the results of a first measurement performed in the Frascati National Laboratories (LNF) of INFN, along with a the results obtained by VIP running at the underground Gran Sasso National Laboratory (LNGS) of INFN. We briefly discuss the results and present future plans to go beyond the present limit by using fast Silicon Drift Detectors (SDD) and a veto system.

We will then conclude the paper by presenting some ideas to use a similar experimental technique to perform measurements of X rays emitted by free electrons, predicted by the spontaneous collapse models.

2. The VIP experiment

VIP is a dedicated experiment for the measurement of the probability of the Pauli Exclusion Principle violation for electrons. The experiment uses the same methods of the Ramberg and Snow experiment (see below), with a much better X-ray detector and in a low-background experimental area - the INFN Gran Sasso underground laboratory. The detector is an array of Charge-Coupled Devices (CCDs), characterized by the excellent background rejection capability, based on pattern recognition and good energy resolution (320 eV FWHM at 8 keV in the present measurement).

2.1. The VIP Experimental Method

The experimental method, originally described in Ref. [14], consists in the introduction of "fresh" electrons into a copper strip, by circulating a current, and in the search for the X-rays resulting from the PEP forbidden radiative transitions that occur if one of these electrons is captured by a copper atom and cascades to a 1S state which is already filled by two electrons. In particular, we are looking for the $2P \rightarrow 1S$ (K_α)transition. The energy of this non-Paulian transition would

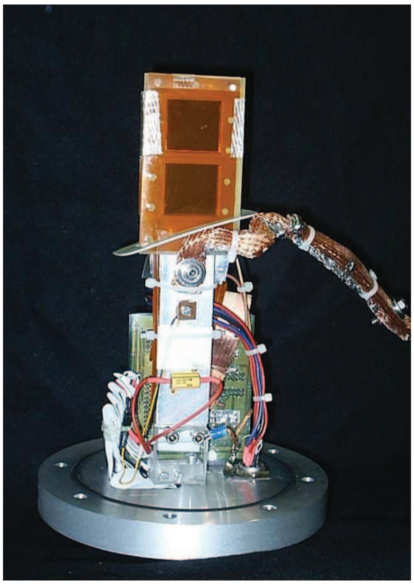

Figure 1. Two CCD detectors used by VIP together with the readout electronics

differ from the normal K_α transition energy by about 300 eV (7.729 keV instead of 8.040 keV) [22], providing an unambiguous signal of PEP violation. The measurement alternates periods without current in the copper strip, in order to evaluate the X-ray background in conditions where no PEP violating transitions are expected to occur, with periods in which current flows in the conductor, when we expect that the "fresh" electrons may lead to Pauli-forbidden transitions.

2.2. The VIP setup

The VIP setup consists of a copper cylinder, 45 mm radius, 50 μm thickness, and 88 mm height surrounded by 16 equally spaced "type 55" CCDs made by EEV [23]. The CCDs are at a distance of 23 mm from the copper cylinder, and paired one above the other (see fig. 1). The setup is enclosed in a vacuum chamber, and the CCDs are cooled to about 168 K by a cryogenic system. The current, provided by an external current supply, flows in the thin cylinder made of ultrapure (99.995%) copper foil from the bottom of the vacuum chamber. The CCDs surround the cylinder and are supported by cooling fingers which protrude from the cooling heads in the upper part of the chamber. The readout electronics is just behind the cooling fingers; the signals are sent to amplifiers on top of the chamber and the amplified signals are read out by ADC boards in the data acquisition computer. More details on CCD-55 performance, as well on the analysis method used to reject background events, can be found in reference [24, 25]. An overall schematic view of the setup is shown in fig. 2.

VIP improved orders of magnitude on the Ramberg and Snow measurement, thanks to the following features:

- use of CCD detectors instead of gaseous detectors, having much better energy resolution (4-5 times better) and higher stability;
- experimental setup located in the clean, low-background, environment of the underground LNGS Laboratory;
- collection of much higher statistics (longer DAQ periods).

We make full use of these features to obtain an improvement of several orders of magnitude on previous limits.

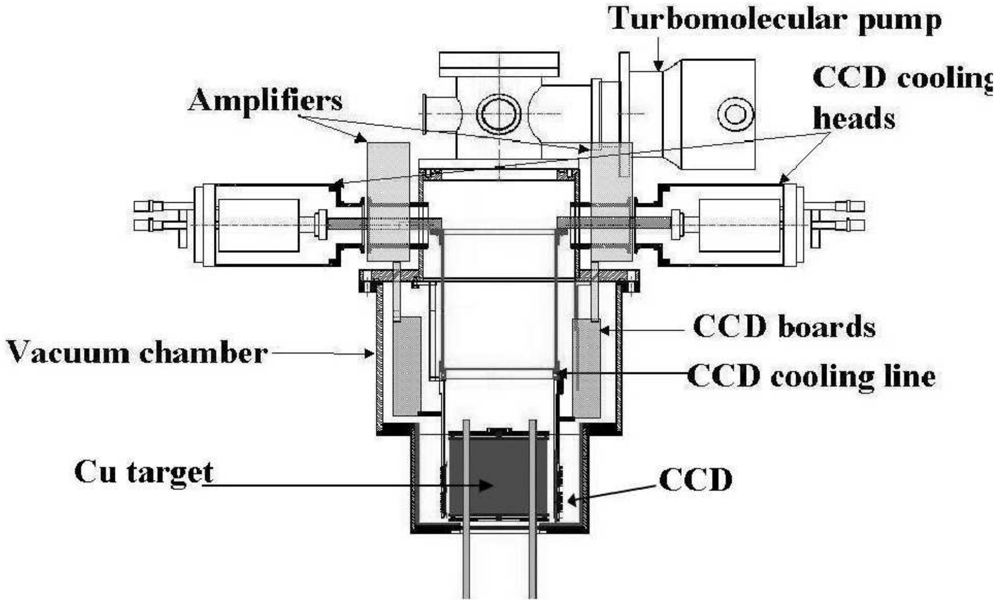

Figure 2. The VIP setup - schematic view

3. The VIP experimental results

The VIP setup was taking data in the low-background Gran Sasso underground laboratory of INFN from 2006 until 2010; presently data analysis is ongoing.

3.1. Results obtained at LNF-INFN

Before installation in the Gran Sasso laboratory, VIP was first prepared and tested at the LNF-INFN laboratory, where measurements were performed in the period 21 November - 13 December 2005. Two types of measurements were performed:

- 14510 minutes (about 10 days) of measurements with a 40 A current circulating in the copper target;
- 14510 minutes of measurements without current.

CCDs were read-out every 10 minutes. The resulting energy calibrated X-ray spectra are shown in figure 3.

These spectra include data from 14 CCD's out of 16, because of noise problems in the remaining 2. Both spectra, apart from the continuous background component, display clear Cu K_α and K_β lines due to X-ray fluorescence caused by the cosmic ray background and natural radioactivity. No other lines are present and this reflects the careful choice of the materials used in the setup, as for example the high purity copper and aluminium, the last one with K-complex transition energies below 2 keV. The subtracted spectrum is shown in Figure 4 a) (whole energy scale) and b) (a zoom on the region of interest). Notice that the subtracted spectrum fluctuates around zero within the statistical error, and is structureless. This not only yields an upper bound for a violation of the Pauli Exclusion Principle for electrons, but also confirms the correctness of the energy calibration procedure and points to the absence of systematic effects.

To extract the experimental limit on the probability that PEP is violated for electrons, $\beta^2/2$, from our data, we used the same arguments of Ramberg and Snow: see references [14] and [26] for details of the analysis. The obtained value is:

$$\frac{\beta^2}{2} < 4.5 \times 10^{-28} \tag{1}$$

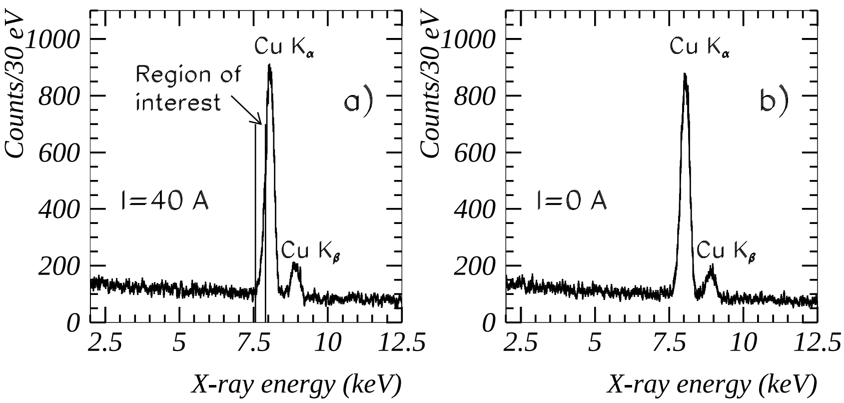

Figure 3. Energy spectra with the VIP setup at LNF-INFN: (a) with current (I = 40 A); (b) without current (I = 0).

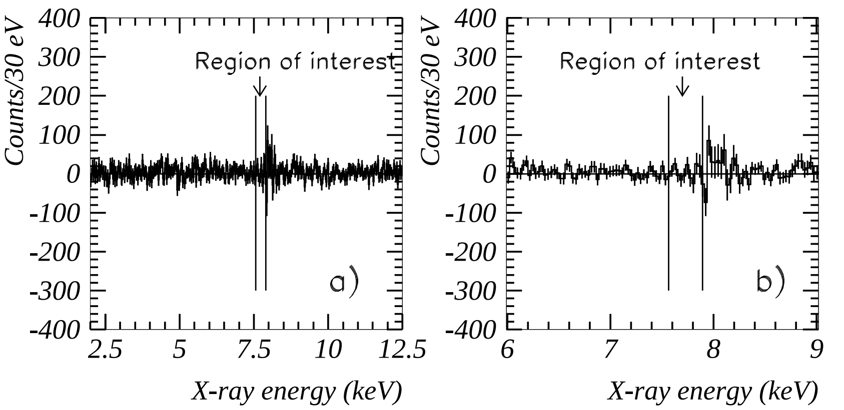

Figure 4. Subtracted energy spectra in the Frascati measurement, *current-on* minus *current-off*, giving the limit on PEP violation for electrons: a) whole energy range; b) expanded view in the region of interest (7.564 - 7.894 keV). No evidence for a peak in the region of interest is found.

Thus with this first measurement in an unshielded environment, we have improved the limit obtained by Ramberg and Snow by a factor ~ 40.

3.2. Experimental results from LNGS

The experiment was installed at LNGS-INFN in Spring 2006 - see figure 5, and was taking data until 2010, alternating period with current on (signal) to periods with current off (background).

A preliminary analysis of the LNGS data gives:

$$\frac{\beta^2}{2} < 4.7 \times 10^{-29} \tag{2}$$

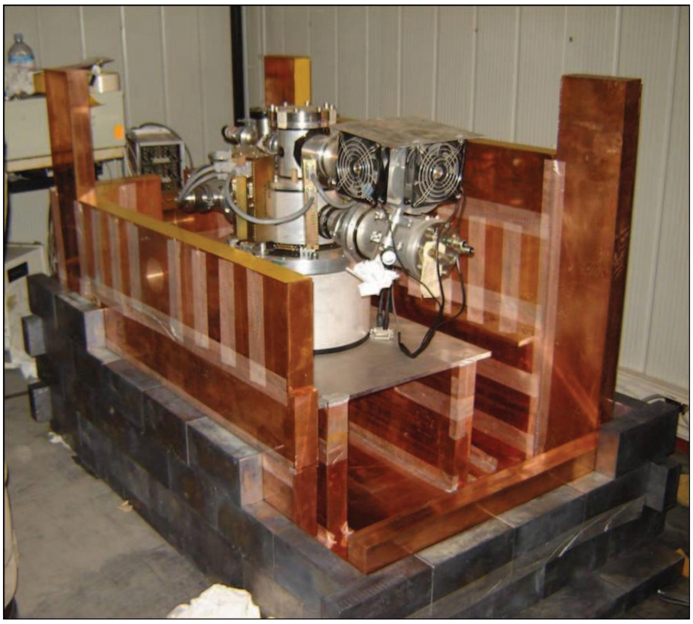

Figure 5. The VIP setup at the LNGS laboratory during installation.

4. Discussion of the results

After the introduction of the straightforward quantum model of Ignatiev and Kuzmin in 1987 [15], Govorkov [27] showed that the model could not work in the wider framework of quantum field theory, because it led to many-particle states with negative norm. The situation changed with the introduction of quon theory [28], which turned out to be a consistent theory of *small* violations of PEP. The basic idea of quon theory is that (anti)commutators are replaced by weighted sums

$$\frac{1-q}{2}\left[a_i, a_j^+\right]_+ + \frac{1+q}{2}\left[a_i, a_j^+\right]_- = a_i a_j^+ - q a_j^+ a_i = \delta_{i,j} \tag{3}$$

where $q = -1$ ($q = 1$) gives back the usual fermion (boson) commutators. The statistical mixture in equation (3) also shows that the PEP violation probability is just $(1+q)/2$ and thus our best experimental bound on q is

$$\frac{1+q}{2} < 4.7 \times 10^{-29} \tag{4}$$

A consistent interpretation of the VIP results can thus be based on quon theory; however here we note that is not easy to devise tests of PEP, because of many conceptual difficulties (see, e.g. [29]), and VIP (and shares some problems of its own with its precursor, the Ramberg and Snow experiment). The main problem lies in the definition of "fresh" electrons: in fact it is unclear how an electron originally injected by the current source into the copper strip can be set apart from the other electrons already present in the strip. One possibility is that some of these "new" electrons have a "wrong wavefunction" in the sense suggested by Rahal and Campa [30]. Yet another possibility is that some localization effect really allows at least a partial identification of electrons: this localization was intuitively rather obvious in the experiment of Goldhaber and Scharff-Goldhaber [31], originally devised to test the identity of β-rays and electrons, later reinterpreted by Reines and Sobel as a test of PEP [32]. In that experiment electrons were injected by a radioactive source, rather than a power supply, and thus the "fresh" electrons were simply those electrons impinging on the target from the radioactive source. This concept of

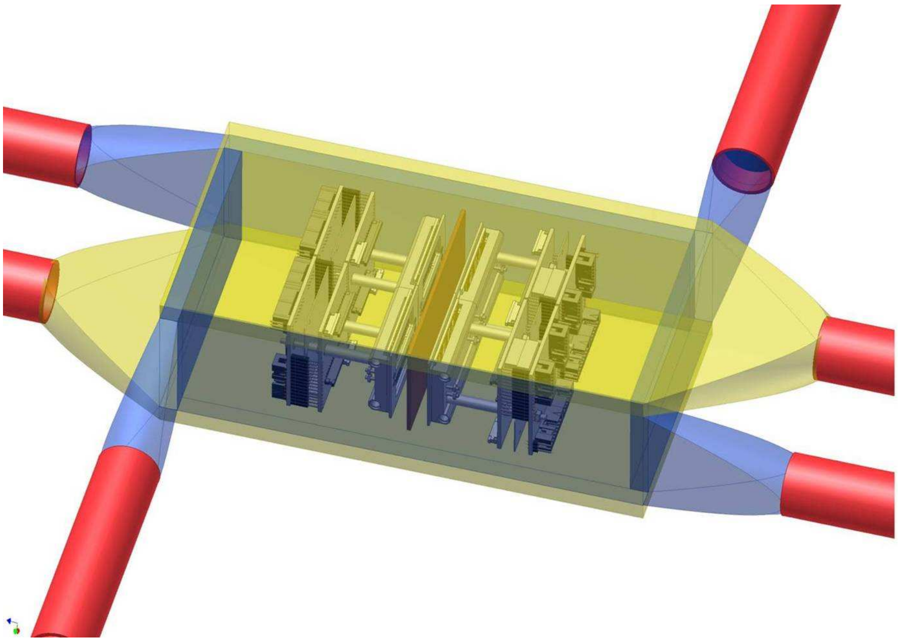

Figure 6. The possible implementation of the upgrade of the VIP experiment using SDD detectors and an external veto-system made of scintillators

novelty is related to electron localizability outside the target, and if an analogous process could be pinpointed for the power supply – which is required to achieve a large statistics, much larger than it is possible with a laboratory radioactive source – then this conceptual problem of VIP (and of the Ramberg and Snow experiment) would fade away. The required localization might be provided by some form of quantum decoherence: Yu and Eberly [33] have shown that in an idealized situation quantum coherence dies off in a finite time just because of quantum noise. Similarly we can conjecture that entanglement of the electron wavefunction in the copper strip could be limited in space and this could let us set apart “old” and “fresh” electrons.

We do not yet have a final answer to these conceptual problems, however we do strongly feel that the test is meaningful and we are now planning an improved version.

5. Upgrade of the VIP setup

The VIP setup used CCD detectors, which are excellent X-ray detectors (good energy resolution, background rejection based on pixel-size) but they are having no timing capability. We plan to switch to a new type of detectors for precision X-rays measurements, the triggerable Silicon Drift Detectors (SSD) which have a fast readout time ($\simeq 1\mu$s) and large collection area (100 mm^2). These detectors were successfully used in the SIDDHARTA experiment [34] for measurements of the kaonic atoms transitions at the DAΦNE accelerator of LNF-INFN; using a proper trigger system a background rejection factor of the order of 10^{-4} was achieved in SIDDHARTA.

With SDD detectors it might then be possible to realize a more compact system and to further reduce the background by using an external veto-system which would eliminate a large part of the background produced by charged particles coming from the outside the setup. A schematic layout of the new setup is shown in fig. 6. Presently, the construction of the setup is under way.

Table 1. Upper bounds on the λ parameter from [35]

Laboratory experiments	Distance (decades) from the enhanced CSL value	Cosmological data	Distance (decades) from the enhanced CSL value
Fullerene diffraction experiments	3-4	Dissociation of cosmic hydrogen	9
Decay of supercurrents (SQUIDS)	6	Heating of Intergalactic medium (IGM)	0
Spontaneous X-ray emission from Ge	-2	Heating of protons in the universe	4
Proton decay	10	Heating of Interstellar dust grains	7

6. Future perspectives: tests of spontaneous collapse models

Having such excellent X-ray detectors as CCDs and SDDs, we are presently considering the possibility to perform in the future measurements of X rays generated as spontaneous radiation predicted by (some) collapse models. The collapse models deal with the "measurement problem" in quantum mechanics, by introducing a new physical dynamics that naturally collapses the state vector. Collapse models make predictions which differ from those of standard quantum mechanics [35]. One of the most exciting task is to perform cutting-edge experiments, in order to asses whether quantum mechanics is exact, or an approximation of a deeper level theory.

In the nonrelativistic collapse model developed by Ghirardi, Rimini, Weber [36] and Pearle [37] (see also ref. [38] for a review), namely the continuous spontaneous localization (CSL) model, the state vector undergoes a nonunitary evolution in which particles interact with a fluctuating scalar field. This interaction has not only the effect of collapsing the state vector towards the particle number density eigenstates in position space, but it increases the expectation value of particle's energy as well. This means, for a free charged particle (as the electron) emission of electromagnetic radiation. This type of phenomenon is predicted by the CSL and is totally absent in the standard quantum mechanics.

Moreover, as shown in [38], the measurement of X rays spontaneously emitted in the collapse models is the most sensitive method to the λ parameter of the collapse; see Table 1 and [35] for related explanations.

In the paper [39] a pioneering work on this spontaneous emission of radiation was performed - the author analysed X-ray data measured in an underground experiment and interpreted them as a limit for the combination of the CSL parameters λ/a^2. It was shown that the highest sensitivity is at few keV X-rays, exactly in the range where our detectors are ideal. We plan to perform a feasibility study to arrive to define a dedicated experiment to measure the X rays predicted by spontaneous collapse models.

6.1. Acknowledgments

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