Found Phys (2010) 40: 765–775
DOI 10.1007/s10701-009-9346-1

The VIP Experimental Limit on the Pauli Exclusion Principle Violation by Electrons

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Received: 13 July 2009 / Accepted: 24 August 2009 / Published online: 18 September 2009

Abstract In this paper we describe an experimental test of the validity of the Pauli Exclusion Principle (for electrons) which is based on a straightforward idea put forward a few years ago by Ramberg and Snow (Phys. Lett. B 238:438, 1990). We perform a very accurate search of X-rays from the Pauli-forbidden atomic transitions of electrons in the already filled 1S shells of copper atoms. Although the experiment has a very simple structure, it poses deep conceptual and interpretational problems. Here we describe the experimental method and recent experimental results, which we interpret in the framework of quon theory. We also present future plans to upgrade the experimental apparatus using Silicon Drift Detectors.

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Keywords Spin-statistics · Violation of the Pauli Exclusion Principle · Atomic (forbidden) transitions · X-ray detectors

1 Introduction

The Pauli Exclusion Principle (PEP) plays a fundamental role in our understanding of a vast array of physical and chemical phenomena, like the structure of the periodic table of elements, the electrical conductivity in metals and the degeneracy pressure which makes white dwarfs and neutron stars stable. This principle is a rather straightforward 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, it remains somewhat mysterious, and, given its basic standing in quantum theory, it is appropriate to carry out precise tests of its validity. Indeed, mostly in the last 15–20 years, several experiments have searched for possible small violations [3–10]. Quite often, these searches originated as by-products of experiments dedicated to different kinds of physics (like, 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.

In 1988 Ramberg and Snow [11] carried out a dedicated search, as they set up an apparatus to detect anomalous X-ray transitions in copper that would point to a small violation of PEP. They interpreted their result in the framework of the simple quantum model of Ignatiev and Kuzmin [12–14], which is essentially a three-level model of fermions, where the violation parameter is the probability amplitude β: the Ramberg and Snow result was the probability $\beta^2/2 < 1.7 \times 10^{-26}$ that PEP is violated by electrons. In recent years the VIP Collaboration set up a much improved version of the Ramberg and Snow experiment, with a higher sensitivity apparatus [15]. Our final aim is to lower 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 [16–20], and decreasing the effect of background by a careful choice of materials, and finally by 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, the outcome of a first measurement performed in the Frascati National Laboratories (LNF) of INFN, along with preliminary results obtained by VIP running at LNGS-INFN After a short discussion of the results we present future plans to go beyond the present limit by using fast Silicon Drift Detectors (SDD) and a veto system, which opens up new possibilities for more refined searches of PEP violation.

2 The VIP Experiment

Although VIP (VIolation of the Pauli Exclusion Principle) is a dedicated experiment, it became feasible when the DEAR (DAΦNE Exotic Atom Research) experiment successfully completed its physics program at the DAΦNE collider at LNF-INFN [21, 22]. DEAR measured X-ray transitions in exotic atoms (kaonic nitrogen and kaonic hydrogen) and used Charge-Coupled Devices (CCD) as detectors. CCD's are almost ideal detectors for X-rays measurements, thanks to their excellent background rejection capabilities, based on pattern recognition, and to their good energy resolution (320 eV FWHM at 8 keV in the present measurement). When the high-grade CCD's of DEAR were no longer in use, they could be used for VIP.

2.1 The Experimental Method

The experimental method, originally described in [11], consists in circulating a large current from an external power supply into a copper strip—and in this way we introduce electrons that were not previously present in the metal lattice—and in the search for the X-rays resulting from the Pauli-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 assume that any electron that has an anomalous wavefunction with respect to those already present in the atom cascades to the ground state just as muons or other particles in exotic atoms [23–25]. In these exotic atoms—for purely statistical reasons—states with high angular momentum are more populated, and eventually the cascade proceeds by almost pure radiative transitions with steps $\Delta n = 1$ and $|\Delta l| = 1$. This means that a whole series of spectral lines should be present, and we search for the most intense of them, the anomalous 2P→1S (K_α) transition (we expect the other lines to be somewhat weakened by the nonradiative steps of the cascade). The energy of this non-Paulian transition would differ from the normal K_α transition energy by about 300 eV (7.729 keV instead of 8.040 keV, as it turns out from a Hartree-Fock-Dirac calculation performed assuming that the anomalous electron behaves like a distinguishable particle, much like a negative muon in an exotic atom [26]), providing an unambiguous signal of PEP violation. The measurement alternates periods without current in the copper strip—to estimate 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 "freshly introduced" electrons may yield Pauli-forbidden transitions.

2.2 The VIP Setup

The VIP setup consists of an annular copper cylinder (45 mm radius, 50 µm thickness, and 88 mm height, see Fig. 1), surrounded by 16 equally spaced "type 55" CCDs made by EEV [27] (these are scientific grade CCDs with 22 µm pixel size). The CCDs are at a distance of 23 mm from the copper cylinder, and paired one above the other (see Fig. 2). The setup is enclosed in a vacuum chamber, and the CCDs are cooled to about 168 K by a cryogenic system. The current 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 [21, 22, 28]. An overall schematic view of the setup is shown in Fig. 3.

Fig. 1 The VIP copper target

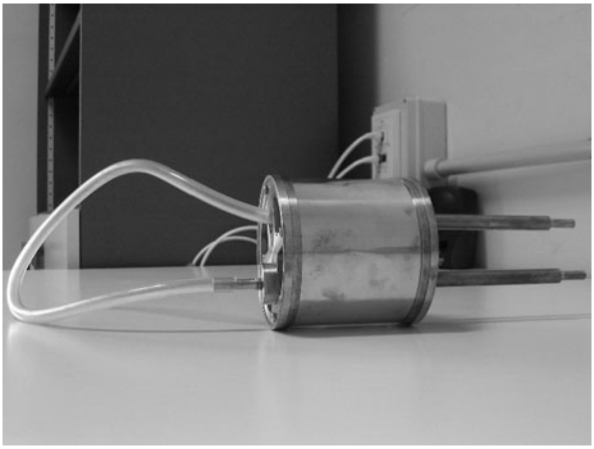
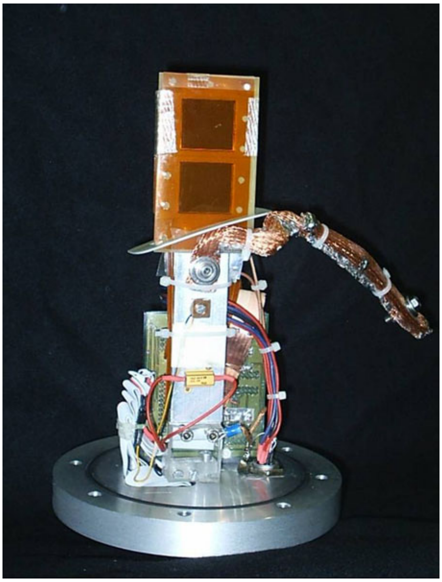


Fig. 2 The CCD unit containing two CCD detectors and part of the readout electronics



We wish to stress that VIP improves very significantly 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, thanks to the stability of CCDs)

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

Fig. 3 The VIP setup—schematic view

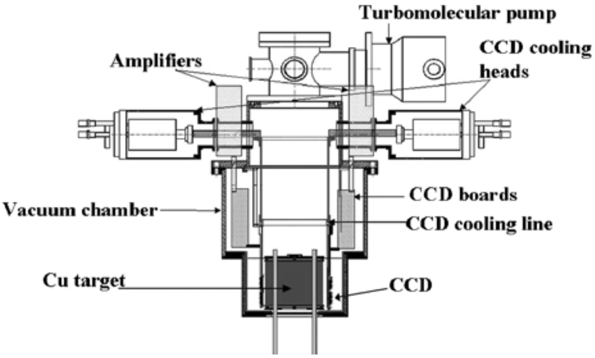
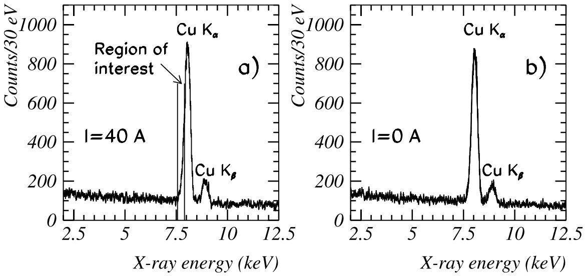


Fig. 4 Energy spectra with the VIP setup at LNF-INFN: (**a**) with current ($I = 40$ A); (**b**) without current ($I = 0$)



3 The VIP Experimental Results

3.1 Results Obtained at LNF-INFN

The VIP setup is presently taking data in the low-background Gran Sasso underground laboratory of INFN. Before installation in the Gran Sasso laboratory, it 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 Fig. 4.

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 high purity aluminum, the last one with K-complex transition energies below 2 keV. The subtracted spectrum is shown in Fig. 5a) (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

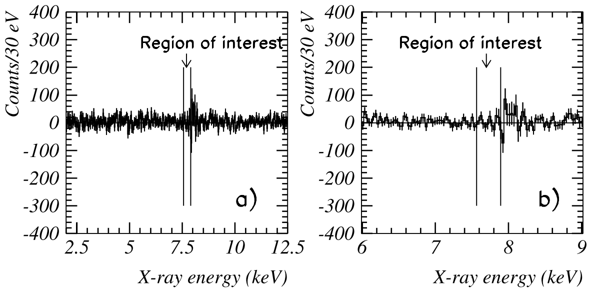


Fig. 5 Subtracted energy spectra in the Frascati measurement, *current-on* minus *current-off*, giving the limit on PEP violation for electrons: (**a**) whole energy range; (**b**) expanded view in the region of interest (7.564–7.894 keV). No evidence for a peak in the region of interest is found

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.

The experimental limit on PEP violation for electrons is expressed by a bound on $\beta^2/2$—which we further discuss in the last section—and to this end we used the same arguments of Ramberg and Snow: see references [11] and [29] for details of the analysis. The obtained value is:

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

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 Preliminary Experimental Results from LNGS

The experiment was installed at LNGS-INFN in Spring 2006 (see Fig. 6), and is presently data taking, alternating period with current on (signal) to periods with current off (background).

We have already established a new limit on PEP violation by electrons from preliminary data taken at LNGS [30]:

$$\frac{\beta^2}{2} < 6 \times 10^{-29}. \tag{2}$$

Data taking will continue till the end of 2009; in parallel we are also working on an improved version of the setup.

4 Discussion and Perspectives

After the introduction of the straightforward quantum model of Ignatiev and Kuzmin in 1987 [12–14], Govorkov [31] 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 Greenberg's quon theory [32], which turned out to be a consistent theory of *small* violations of PEP. The

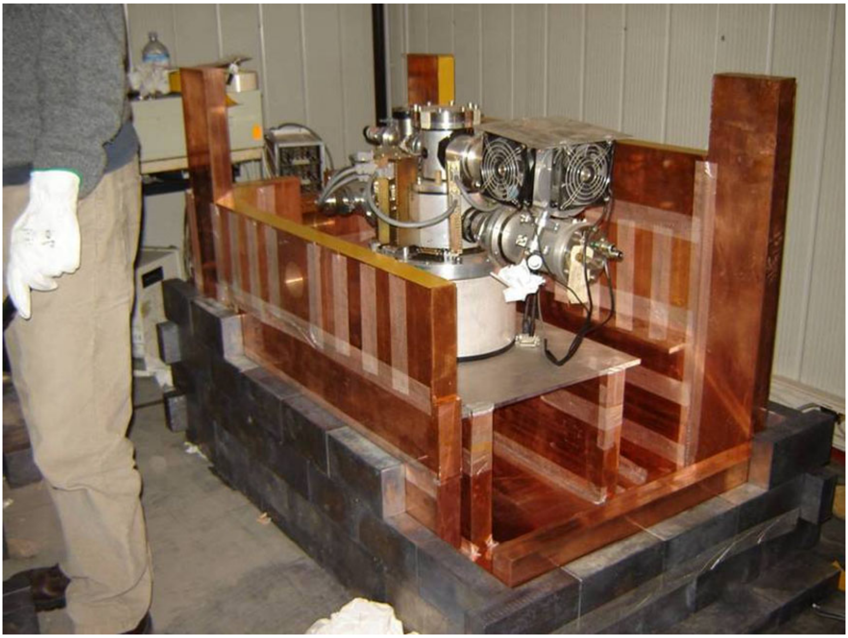


Fig. 6 The VIP during the installation at the Gran Sasso underground laboratory

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 (3) also shows that the PEP violation probability is just $(1+q)/2$ [33] and thus our best experimental bound on q is

$$\frac{1+q}{2} < 6 \times 10^{-29}. \tag{4}$$

We remark that calculations by Hilborn [34, 35] on spin-statistics-violating transitions in multiphoton systems, indicate that a factor $(1+q)^2$ instead of $(1+q)$ may actually appear in the final formulas for transition probabilities. Although similar calculations have never been carried out for multielectron systems, there are strong hints that the same arguments apply in this case as well: if this is so, the bound on q must be revised

$$(1+q) < 10^{-14}. \tag{5}$$

Here we note that is not easy to devise tests of PEP, because of many conceptual difficulties (see, e.g. [36]), e.g., it is not possible to generate the violation dynamically, it must preexist, because the transition Hamiltonian must be symmetric and cannot change the symmetry properties of the physical system—in our case the copper atoms in the strip. VIP also shares with its precursor, the Ramberg and Snow experiment, another difficulty, which lies in the definition of "fresh" electrons: in fact it is unclear how an electron originally injected by the power supply 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 belong to the subset with a "wrong wavefunction" in the sense suggested by Rahal and Campa [37]. 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 [38], originally devised to test the identity of β-rays and electrons, and later reinterpreted by Reines and Sobel as a test of PEP [39]. 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 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 [40] 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 allow us to set apart "old" and "fresh" electrons and reestablish a clear similarity with the experiment of Goldhaber and Scharff-Goldhaber.

At the moment these are just speculations, 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. The present VIP setup uses CCD detectors which are excellent X-ray detectors (good energy resolution, background rejection based on pixel-size) but they are integrating detectors, like photographic film—and thus they provide only a very rough time resolution (about 1 minute). 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 µs) and large collection area (100 mm^2). These detectors, see Fig. 7, are at present success-

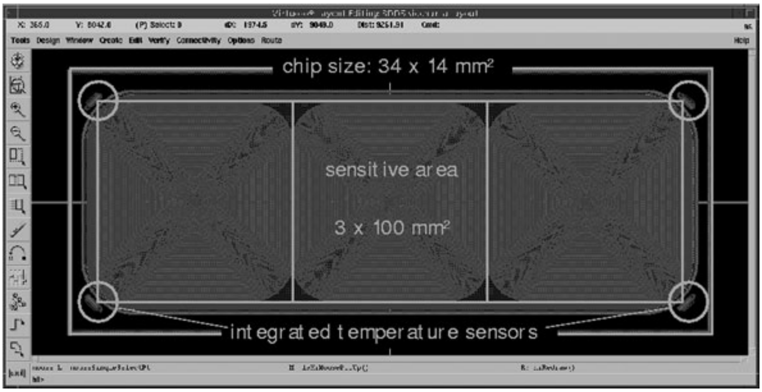


Fig. 7 SDD layout on the readout side: 3 SDD cells, independently read, each with an area of 100 mm^2

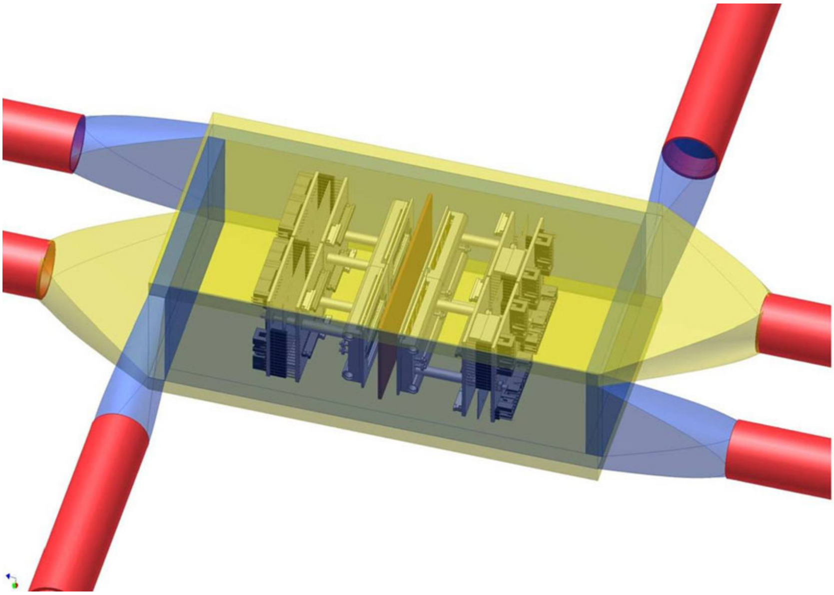


Fig. 8 Schematic drawing a possible implementation of the upgrade of the VIP experiment using SDD detectors and an external veto-system. Six paired scintillation detectors form a tight “veto box” that acts as an anticoincidence detector for the SDDs. This sketch shows a planar geometry for the copper strip and the mosaic of SSDs, but this is not yet final, as the decision depends on how to best maximize the solid angle of the detectors, and at the same time make detector and copper strip cooling as efficient as possible

fully used in the SIDDHARTA experiment [41] 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 SIDDARTHA.

With these new detectors is then possible to further reduce the background by using an external veto-system which should allow the elimination of all background produced by charged particles from the outside. A schematic layout of the new setup is shown in Fig. 8. Presently, experimental tests are under way to define the new experimental setup, which will be more compact than the present VIP setup and, as such, more manageable.

Acknowledgements The VIP Collaboration wishes to thank all the LNGS laboratory staff for the precious help and assistance during all phases of preparation, installation and data taking.

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