The VIP experiment

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VIP experiment

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Abstract. The VIP (Violation of the Pauli Exclusion Principle) experiment is dedicated to check the validity of one of the basic principles of modern physics. This investigation is done searching for anomalous X-rays emitted by copper atoms in a conductor: any detection of these anomalous X-rays would mark a Pauli forbidden transition. VIP is currently taking data at the Gran Sasso underground laboratories, and its scientific goal is to improve by three-four orders of magnitude the previous limit on the probability of Pauli violating transitions, bringing it into the $10^{-29}$–$10^{-30}$ region. The new experimental results and future plans are presented.

1. Introduction

The Pauli Exclusion Principle (PEP), direct consequence of the spin-statistics connection [1], has been tested in the last years by several experiments [2, 3, 4, 5, 6]. Regarding the violation of PEP for electrons, in 1988 Ramberg and Snow (RS) [7] performed a dedicated experiment, searching for anomalous X-ray transitions due to a small possible violation of PEP in a copper conductor. They established an upper limit on the probability for an electron circulating in the conductor to form a mixed symmetry state with the already present copper electrons as $\beta^2/2 \leq 1.7 \times 10^{-26}$.

2. The Experiment

The idea of the experiment was first suggested by George Snow [7] and was put forward in a paper of Greenberg and Mohapatra [8]: if there are electron states with wavefunctions with mixed symmetry, and if some electrons sit in the ground states of some atoms while others are free, then the free electrons may be captured in the ground atomic states, even though the ground (1S) states may already be filled with electron pairs. Such a radiative capture process is accompanied
by the emission of X-rays, and because of the anomalous atomic electron configuration these X-rays differ from the characteristic X-rays emitted by the atom. The detection of these anomalous X-rays would indicate that non-Paulian atoms exist and would demonstrate a violation of the Pauli Exclusion Principle. One might argue that if such mixed symmetry states exist, any anomalous pair in a block of material should already fill the ground states of the atoms in the block and therefore no detection should be expected: George Snow suggested that one could reestablish a non-equilibrium situation simply by injecting fresh electrons with an external source, such as a current source. The current source substitutes the radioactive $\beta$-source in the experiment of Goldhaber and Scharff-Goldhaber [9] (as reinterpreted by Reines and Sobel[10]), which was actually the first search for anomalous X-rays.

VIP is a dedicated experiment for the measurements of the probability of the Pauli Exclusion Principle violation for electrons which uses the same methods like the Ramberg and Snow experiment, with a much better soft X-ray detector in a low-background experimental area - the INFN Gran Sasso underground laboratory. The detector consist of Charge-Coupled Devices (CCD), caracterized by the excellent background rejection capability, based on pattern recognition and good energy resolution (320 eV FWHM at 8 keV in the present measurement) [11].

The experimental method consists in the introduction of new electrons into a copper strip, by circulating a current, and in the search for X-rays resulting from the $2p \rightarrow 1s$ anomalous radiative transition that occurs if one of the new electrons is captured by a copper atom and cascades down to the 1s state already filled by two electrons of opposite spin. The energy of the $2p \rightarrow 1s$ transition, calculated with a multiconfiguration Dirac-Fock method with an estimated error smaller than 10 eV [12], would differ from the normal $K\alpha$ transition by about 300 eV (7.729 keV instead of 8.04 keV), providing an unambiguous signal of the 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, to periods in which current is flown in the conductor, thus providing new electrons, which may possibly violate PEP. The rather straightforward analysis consists in the evaluation of the statistical significance of the normalized subtraction of the two spectra in the energy region of the PEP-violating transition.

3. Results
3.1. First Experimental Results
The first results were obtained in the period 21 November - 13 December 2005, at the Frascati National Laboratories of INFN, Italy, before moving and installing the apparatus at Gran Sasso National Laboratories(LNGS). 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 circulating current,

where CCD’s were read-out every 10 minutes. The resulting calibrated in energy X-ray spectra are shown in figure 1. These spectra include data from 14 CCD’s out of 16, because of noise problems in the remaining 2.

Both spectra, apart of the continuous background component generated by the cosmic ray background and natural radioactivity, display clear Cu $K\alpha$ and $K\beta$ lines due to X-ray fluorescence also 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 aluminium.

The subtracted spectrum is shown in Figure 2 a) (whole energy scale) and b) (a zoom on the region of interest). Notice that the subtracted spectrum is normalized to zero within statistical
Figure 1. Energy spectra in the Frascati measurement: a) energy spectrum for the measurement with current (I=40 A); b) energy spectrum for the measurement without current.

error, and is structureless.

Figure 2. Subtracted energy spectra in the Frascati measurement, current minus no-current, 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.

The notation of Ignatiev and Kuzmin [13], which has been incorporated in the paper of Greenberg and Mohapatra [8], was used: even though the model of Ignatiev and Kuzmin has been later shown to be incompatible with quantum field theory [14], the parameter $\beta$ that measures the degree of PEP violation in the Ignatiev and Kuzmin model has stuck and is still found in the literature, also because it is easy to show that it is related to the parameter $q$ of quon theory, by the relation [15]: $(1 + q)/2 = \beta^2/2$ (in quon theory, $-1 \leq q \leq 1$, where $q = -1$ corresponds to fermions and $q = 1$ corresponds to bosons, so that here $q$ must be close to -1 and $(1 + q)/2$ must be very small, because we are dealing with electrons). Moreover, this parametrization was used for an easy comparison of our results with the RS experiment, which utilized the same formalism. To determine the experimental limit on $\beta^2/2$ from our data, using the same arguments of Ramberg and Snow [7, 16], we found [16]:

$$\frac{\beta^2}{2} \leq 4.5 \times 10^{-28} \text{ at 99.7% CL.}$$
3.2. Preliminary LNGS updated results

In order to reduce the background, the apparatus is currently installed in the LNGS underground laboratory, to reduce cosmic rays interactions, while the effects of natural radioactivity are moderated by a massive shield built by low-activity materials. The results presented here are based on one year of data acquisition, in the above-mentioned conditions. Our data consist of two periods of data acquisition:

• 236005 minutes of measurements with a 40 A current circulating in the copper target;
• 172685 minutes of measurements without circulating current,

Performing the analysis as described in the previous section, from the subtracted spectra we find the new preliminary value for the violation parameter:

\[ \beta^2 \leq 6 \times 10^{-29} \text{ at } 99.7\% \text{ CL.} \]

improving the limit obtained by Ramberg and Snow by a factor about 250. Today this is the best value ever reached on the probability of PEP violation for the electrons.

4. Conclusions and Perspectives

A new measurement of the PEP violation limit for electrons is being performed by the VIP experiment. The search of a tiny violation is based on a measurement of PEP violating X-ray transitions in copper, under a circulating 40A current. A new limit for the PEP violation for electrons was established: \(4.5 \times 10^{-28}\), lowering by about two orders of magnitude the previous one [7]. We have installed VIP at LNGS in spring 2006 and started the data-taking in reduced background condition. After one year of data taking the LNGS preliminary limit for the PEP violation for electrons was lowered to \(6.0 \times 10^{-29}\), about three orders of magnitude better than the RS experiment. Data acquisition will continue at LNGS with the goal of bringing the limit on PEP violation for electrons into the \(10^{-30}\) region, which is of particular interest [17] for all those theories related to possible PEP violation coming from new physics.

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