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Search for the violation of Pauli Exclusion Principle at LNGS

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Abstract. In the VIP (VIolation of Pauli exclusion principle) and its follow-up VIP-2 experiments at the Laboratori Nazionali del Gran Sasso, we test the validity of the Pauli Exclusion Principle, by searching for x-rays from copper atomic transitions from a $2p$ orbit electron to the ground state which is already occupied by two electrons. Such transitions are prohibited by the Pauli Exclusion Principle. The physics run of the VIP-2 experiment started in late 2016 and will collect data for three years. From the first data taking period of two months we have obtained a new limit better than the VIP result from three years of running. In this article we present the published first physics result from the VIP-2 experiment and discuss about the future perspectives.

1 Introduction

The Pauli Exclusion Principle (PEP) is one of the fundamental building blocks of Quantum Mechanics. Its validity is manifested in the periodic table of elements, electric conductivity in metals, the degeneracy pressure which makes white dwarfs and neutron stars stable, as well as many other phenomena in physics, chemistry and biology. In quantum mechanics, the violation of PEP is equivalent

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to the violation of spin-statistics [1] [2] [3], and experimentally to the existence of states of particles that follow statistics other than the fermionic or the bosonic ones.

The experimental and theoretical searches for a small violation of the PEP or the violation of spin-statistics are reviewed exhaustively for example in [3] and [4], which all pointed out a notable fact that there exists no established model in quantum field theory that can include small violations of the PEP explicitly. Moreover, although many limits for the violation have been presented by experimental searches, the parameters that quantify the limits cannot be directly compared since they are dependent on the model/system that the experiments based upon. In this context, the experimental method introduced by Ramberg and Snow [5] is considered as one of the direct tests of the PEP as reviewed in [4]. In their original experiment, by running a high electric DC current through a copper conductor, they searched for x-rays from transitions that are PEP-forbidden after electrons are captured by copper atoms. In particular, candidate events are the transitions of electrons from the $2p$ level to an abnormal $1s$ level, which is already occupied by two electrons, violating the PEP explicitly. Due to the shielding effect of the additional electron in the $1s$ level, the energy of such abnormal transitions will deviate from the copper $K\alpha$ x-ray at 8 keV by about 300 eV [6], which are distinguishable in precision spectroscopical measurements. Since the *new* electrons from the current are supposed to have no a-priori established symmetry with the electrons inside the copper atoms, the detection of the energy-shifted x-rays is an explicit indication of the violation of spin-statistics, and thus the violation of the PEP for electrons.

In section 2, we will discuss about the VIP and the VIP-2 experiments at Laboratori Nazionali del Gran Sasso (LNGS), and in section 3 we introduce the first physics result from VIP-2 that we have published recently in [7]. Finally we discuss the future perspectives briefly in section 4.

2 VIP-2 experiment

Performed at the LNGS-INFN underground laboratory, the VIP experiment used a similar method as that of the Ramberg and Snow, and defined the parameter to represent the probability that the PEP is violated in the same way, so that a direct comparison of the experimental results is possible. Two main factors improved the sensitivity significantly in VIP experiment. Firstly, by performing the experiment in the low radioactivity laboratory at LNGS, the background originated from cosmic rays is drastically reduced due to the shielding of the mountain rocks. Secondly, the application of Charge Coupled Device (CCD) as the x-ray detector with a typical energy resolution of 320 eV at 8 keV, increased the precision in the definition of the region of interest to search for anomalous x-rays. The VIP experiment set the limit for the probability of the PEP violation for electrons to be 4.7×10^{-29} [8].

We plan to further improve the sensitivity by two orders of magnitude in the VIP-2 experiment, by using new x-ray detectors and an active shielding of scintillators. The major improvements come from the change of the layout of the copper strip target and of the x-ray detectors, which allow a larger acceptance for the x-ray detection. Secondly a DC current with 100 A is applied instead of 40 A, which introduces twice more new electrons into the copper strip. Last but not least, in addition to the improved passive shielding surrounding the setup to reduce the background generated by the environmental radiations, the use of Silicon Drift Detector (SDD) as the x-ray detectors allows to implement an active shielding using scintillators, which removes the background induced by the high energy charged particles that are not shielded. The experimental setup and the performance of the detectors of VIP-2 are described in detail in [7] [9] [10] [11] [12].

We defined the trigger for data taking as either an event at any SDD or a coincidence between two layers of the veto detector, and implemented the logic using the NIM standard modules. A VME-based data acquisition system records the energy deposit of the six SDDs, the charge to digital signals

(QDC) of the 32 scintillator channels, and the timing information of the SDDs with respect to the main trigger in the data. The data acquisition system allows remote access and control from the computer terminals outside the Gran Sasso laboratory.

Exhaustive tests for the detectors and the setup were performed both in the laboratory above ground and inside the barrack at LNGS before the physics run. From October 2016 we started the first campaign of data taking with the complete detector system. An in-situ energy calibration for the SDDs was realized, by placing near the detectors a weak Iron-55 source covered by a 25 um thick titanium foil. The manganese K-series x-rays from the source partly go through the foil and partly irradiate the foil generating titanium K-series x-rays. These fluorescence x-rays are detected by the SDDs at an overall rate of about 2 Hz, and provide reference energy peaks to calibrate the digitized SDD signals to energy scale.

3 First result of the VIP-2 experiment

In the data taking camaign from October to December 2016, we took data both with 100 A DC current to search for PEP violating events, and with similar amount of time without current to determine the background. The energy calibrations for the SDDs were performed for each data subset which corresponds to a period of about one week. Then the energy spectra were summed over the whole data taking period, separately for the 100 A current-on data and current-off data sets. The spectra that correspond to 34 days of effective data acquisition with 100 A current on and 28 days with current off are shown in Figure 1 [7], in which the fluorescence lines of titanium and manganese are labeled.

The K-series x-rays from the de-excitation of the copper, when the copper conductor or the strip inside the setup is irradiated by the environmental radiations and high energy particles from cosmic rays, contribute to the main background near the energy region of interest (ROI in Figure 1) from 7629 eV to 7829 eV. The range of the ROI is defined by the SDD energy resolution (200 eV FWHM) at the K_α copper transition energy 8.04 keV, and the center of the ROI is the expected value of the PEP violating transition. To obtain the number of PEP violating events in the ROI, the current-off spectrum was normalized to 34 days of data taking time, and then a subtraction from the current-on spectrum gave the numbers of x-rays in the region of interest as :

- with I = 100 A; $N_X = 2222 \pm 47$ (for 34 days of data taking);
- with I = 0 A; $N_X = 2181 \pm 47$ (28 days of data taking normalized to 34 days);
- numerical subtraction : $\Delta N_X = 41 \pm 66$ (normalized to 34 days of data taking time).

The number of possible PEP violating events, ΔN_X, is related to the $\beta^2/2$ parameter which represents the probability of PEP violation [13], following the similar notations used by Ramberg - Snow and later by the VIP experiment :

$$\begin{aligned}\Delta N_X &\geq \frac{1}{2}\beta^2 N_{new}\frac{1}{10}N_{int} \times (\text{detection efficiency factor}) \\ &= \frac{\beta^2(\Sigma I\Delta t)D}{e\mu}\frac{1}{20} \times (\text{detection efficiency factor}). \qquad (1)\end{aligned}$$

Furthermore, the electric charge e of the electron, the intensity I of the applied DC current, and the duration time Δt of the measurement, give the number of new electrons that pass through the conductor :

$$N_{new} = (1/e)\Sigma I\Delta t, \qquad (2)$$

The minimum number of internal scattering processes between a new electron and the atoms of the copper lattice, N_{int}, is of order D/μ, where D is the length of the copper strip (10 cm), and μ is the

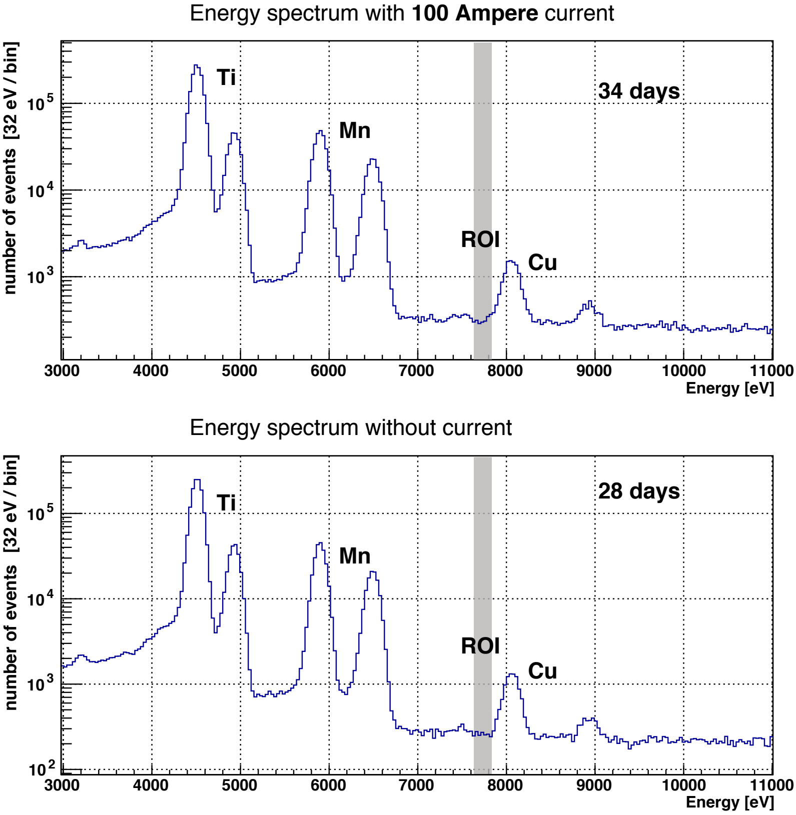

Figure 1. The energy spectra from all the SDDs, taken during the physics run in 2016 at LNGS [7]. Anticipated PEP-violating events, if exist, shall occur in the region of interest (ROI) when the DC current is applied.

mean free path of electrons in copper. The capture probability of a new electron by an atom of the copper lattice is greater than 1/10 of the scattering probability, which is the same assumption used in the VIP paper [14].

The detection efficiency factor was determined to be about 1%, evaluated with a Monte Carlo simulation based on Geant4.10 with realistic detector configuration. The following factors are taken into account in the simulation : the transmission rate of a copper K_α x-ray that origins at a random position inside the copper strip and reaches the surface; the geometrical acceptance of the photons coming from the surface of the copper stipe arriving at the six SDD detectors; the detection efficiency of a copper K_α x-ray by the 450 um thick SDD unit.

With $D = 10$ cm, $\mu = 3.9 \times 10^{-6}$ cm, $e = 1.602 \times 10^{-19}$ C, $I = 100$ A, and normalizing the measurement time with current to 34 days, using the three sigma upper bound of $\Delta N_X = 41 \pm 66$ to give a 99.7% C.L., we get an upper limit for the $\beta^2/2$ parameter :

$$\frac{\beta^2}{2} \leq \frac{3 \times 66}{4.7 \times 10^{30}} = 4.2 \times 10^{-29}. \tag{3}$$

This is the best result up to date, and will be further improved by the end of the three years data taking of the VIP-2 experiment.

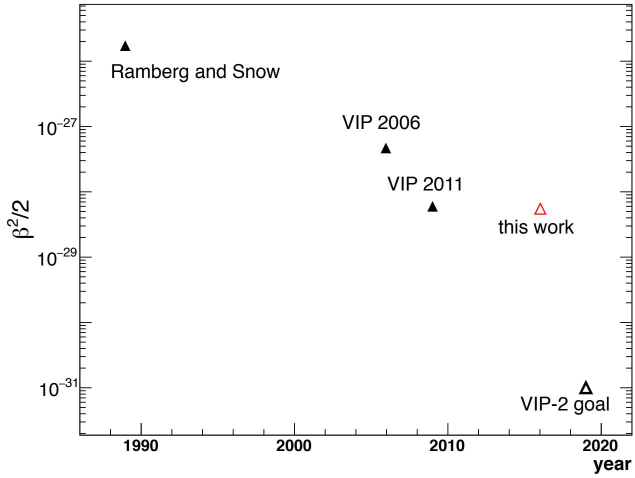

Figure 2. All the past results from PEP violation tests for electrons with a copper conductor, including the result from this work [7]. With three years of operation the VIP-2 experiment can either reach the anticipated sensitivity goal, or find the PEP violation.

4 Future Perspectives

From the successful first physics run with two months of data taking, the VIP-2 experiment has already given a better limit than the VIP result obtained from three years of running, as shown in Figure 2 [7] which includes all the past experimental results of the PEP violation tests for electrons using the method first developed by Ramberg and Snow. After the install of the full passive shielding to further remove the environmental background and the geometrical modification for larger detection efficiency, in the planned data taking time of 3 years, the VIP-2 experiment can either set a new upper limit for the probability that the PEP is violated at the level of 10^{-31}, further improving the current result by two orders of magnitude, or find the PEP violation, which would have profound impact in research fields beyond physics.

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