VIP

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1 The VIP scientific case and the experimental method

The Pauli Exclusion Principle (PEP), a consequence of the spin-statistics connection, 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. Although the principle has been spectacularly confirmed by the huge number and accuracy of its predictions, its foundation lies deep in the structure of quantum field theory and has defied all attempts to produce a simple proof. Given its basic standing in quantum theory, it is appropriate to carry out high precision tests of the PEP validity and, indeed, mainly in the last 20 years, several experiments have been performed to search for possible small violations. Many (if not all) of these experiments are using methods which are not obeying to the so-called Messiah-Greenberg superselection rule. Moreover, the indistinguishability and the symmetrization (or antisymmetrization) of the wave-function should be checked independently for each particle, and accurate tests were and are being done.

The VIP (VIolation of the Pauli Exclusion Principle) experiment, an international Collaboration among 9 Institutions of 6 countries, has the goal to either dramatically improve the previous limit on the probability of the violation of the PEP for electrons, (P $< 1.7 \times 10^{-26}$ established by Ramberg and Snow: *Experimental limit on a small violation of the Pauli principle*, Phys. Lett. **B 238** (1990) 438) or to find signals from PEP violation, by exploring a region where new theories could allow for the PEP violation.

The experimental method consists in the introduction of electrons into a copper strip, by circulating a current, and in the search for X-rays resulting from the forbidden radiative transition that occurs if some of the new electrons are captured by copper atoms and cascade down to the 1s state already filled by two electrons with opposite spins. The energy of *2p* $\rightarrow$ *1s* transition would differ from the normal K_α transition by about 300 eV (7.729 keV instead of 8.040 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, with periods in which current flows in the conductor, thus providing "new" electrons, which might violate PEP. The rather straightforward analysis consists in the evaluation of the statistical significance of the normalized subtraction of the two spectra in the region of interest (if no signal is seen).

The experiment is being performed at the LNGS underground Laboratories, where the X-ray background, generated by cosmic rays, is reduced.

The VIP group is considering also the extension of its scientific program to the study of the collapse models, by the measurements of the spontaneous radiation (X rays), predicted by these models. Very encouraging preliminary results were obtained.

2 The VIP experimental apparata

The first VIP setup was realized in 2005, starting from the DEAR setup, reutilizing the CCD (Charge Coupled Devices) as X-ray detectors, and consisted of a copper cylinder, were current was circulated, 4.5 cm in radius, 50 μm thick, 8.8 cm high, surrounded by 16 equally spaced CCDs of type 55.

Figure 1: The VIP setup at the LNGS laboratory during installation.

The CCDs were placed at a distance of 2.3 cm from the copper cylinder, grouped in units of two chips vertically positioned. The setup was enclosed in a vacuum chamber, and the CCDs cooled to 165 K by the use of a cryogenic system. The setup was surrounded by layers of copper and lead to shield the setup against the residual background present inside the LNGS laboratory, see Fig. 1.

The DAQ alternated periods in which a 40 A current was circulated inside the copper target with periods without current, referred as background.

VIP was installed at the LNGS Laboratory in Spring 2006 and was taking data in this configuration until Summer 2010. In 2011 we started to prepare a new version of the setup, VIP2, installed in 2015 at the LNGS-INFN, with which we will gain a factor about 100 in the probability of PEP violation in the coming years.

3 Activities in 2015

3.1 VIP2 - a new high sensitivity experiment

In order to achieve a signal/background increase which will allow a gain of two orders of magnitude for the probability of PEP violation for electrons, we built a new setup with a new target, a new cryogenic system and using new detectors with timing capability and an active veto system. As X-ray detectors we use Silicon Drift Detectors (SDDs) which were employed in the SIDDHARTA experiment measuring kaonic atoms at the DAΦNE electron-positron collider of Laboratori Nazionali di Frascati. SDDs have an even better energy resolution than CCDs and provide as well timing capability which allow to use anti-coincidence operation with scintillators and therefore an active shielding. The VIP2 system will provide:

1. signal increase with a more compact system with higher acceptance and higher current flow

Table 1: List of expected gain factors of VIP2 in comparison to VIP (given in the brackets).

Changes in VIP2	value VIP2(VIP)	expected gain
acceptance	12%	12
increase current	100A (50A)	2
reduced length	3 cm (8.8 cm)	1/3
total linear factor		8
energy resolution	170 eV(340 eV)	4
reduced active area	6 cm^2(114 cm^2)	20
better shielding and veto		5-10
higher SDD efficiency		1/2
background reduction		200-400
overall gain		**∼120**

in the new copper strip target;

2. background reduction by decreasing the X-ray detector surface, more compact shielding (active veto system and passive), nitrogen filled box for radon radiation reduction.

In the table 1 the numerical values for the improvements in VIP2 are given which will lead to an expected overall improvement of a factor about 100.

3.2 Status of VIP2 in 2015

From 2014 to 2015, we finished the production of 32 pieces of veto detectors made of plastic scintillators coupled to Silicon PhotoMmultipliers(SiPM). The preamplifiers for the SiPMs were fine tuned and with the veto detectors we took background data inside the laboratory. The six SDD elements with a total active area of 6 cm^2 were mounted inside the vacuum chamber and cooled down to 110 K, and we successfully took calibration data using an Fe-55 source. All the SDDs were performing according to expectation with an energy resolution of about 150 eV (FWHM) at 6 keV.

We define the trigger for data taking by either an event at any SDD or a coincidence between two layers of the veto detector. The trigger logic was implemented using the NIM standard modules and a VME-based data acquisition system was customized. From the cosmic ray events that produce coincidences between the veto scintillators and the SDDs, we confirmed the time correlation whose spread is characterized by the drift time of the SDD of less than 1 μs.

To make sure the heat from the Cu conductor when the electric current is applied does not affect the silicon detectors nearby, we monitored the temperatures of the setup while applying an electric current up to 80 Ampere. A water chiller with cooling capacity less than 900 W was confirmed to be sufficient to keep the Cu at the room temperature level.

The series of tests for the detectors, the trigger logic and the slow control/monitors have confirmed that the expected performances of the apparatus, as listed in Table 1, were reached. In November 2015, we transported the full setup to the VIP-2 experiment site in Gran Sasso. We assembled the cryogenic system and the readout logic as shown in Fig. 3 and started the test run.

As an important step to confirm the operation of the SDDs after the transportation, we took calibration data by shining 22 keV X-rays on Zr and Ti foils placed near the SDDs. The spectra

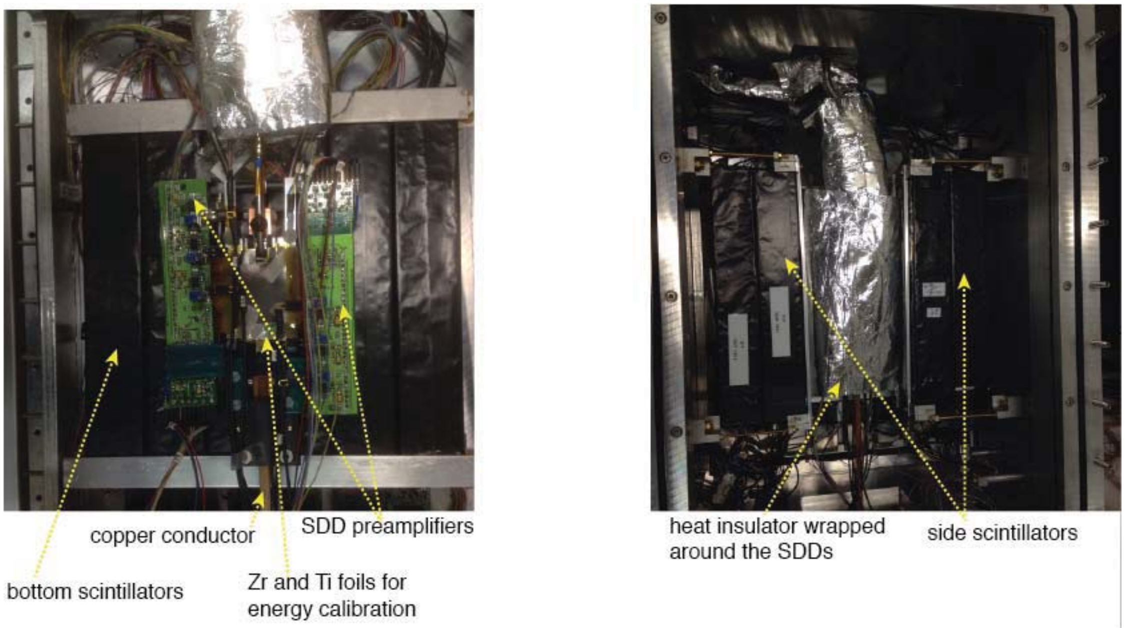

Figure 2: Pictures of the detectors inside the setup. Left : a top view of the setup after the SDDs and their preamplifier board were mounted close to the Cu conductor; the bottom layer of scintillators is also visible in the background; right : same angle of view after the heat insulator was wrapped around the SDDs, and the side layer of scintillators were mounted.

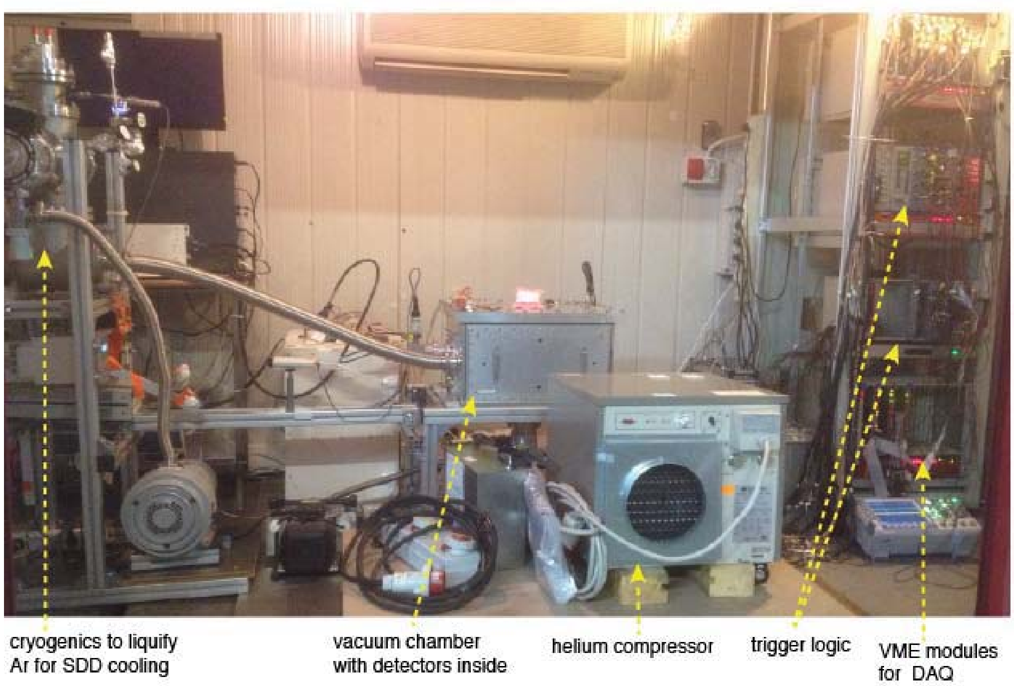

Figure 3: A picture of the VIP-2 setup in the barrack at LNGS as in November 2015.

obtained are shown in Fig. 4, where all SDDs were in working condition and a preliminary analysis showed that the energy resolution is compatible to the one obtained in the tests in the laboratory. We are presently in data taking at LNGS

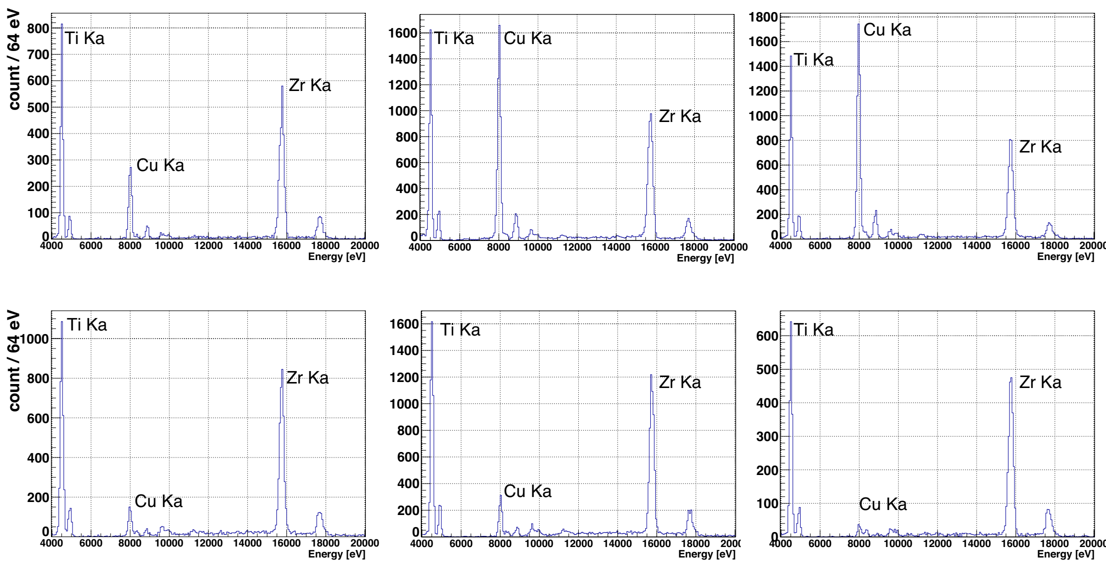

Figure 4: Energy spectra of SDDs from a calibration run in the VIP barrack at LNGS. The relative intensity of the Cu Ka varies due to geometrical reason.

3.3 Workshops organization

In 2015 the following workshop related to the physics of VIP, and, more generally, to quantum mechanics, was organized at LNF-INFN:

1. "Is quantum theory exact? The endeavor for the theory beyond standard quantum mechanics - FQT2015", LNF-INFN, 23-25 September 2015.

The results and the future plans for VIP2 were discussed, together with new directions which might be of interest for the Collaboration.

4 Activities in 2016

In 2016 will be in data taking with VIP2 at LNGS-INFN. We are, as well, going to continue the studies on the collapse model (as a solution of the measurement problem, put initially forward by Ghirardi, Rimini and Weber) by measurements of X rays spontaneously emitted in the continuous spontaneous localization (CSL) model.

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5 Publications

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2. A. Pichler *et al.*, VIP 2: Experimental tests of the Pauli Exclusion Principle for electrons, e-Print: arXiv:1602.00867 [physics.ins-det].

3. C. Curceanu *et al.*, Spontaneously emitted X-rays: an experimental signature of the dynamical reduction models, Found. of Phys., 46 (2016) 263, DOI: 10.1007/D10701-015-9923-4.

4. H. Shi *et al.*, Searches for the Violation of Pauli Exclusion Principle at LNGS in VIP(-2) experiment, e-Print: arXiv:1601.05828 [physics.ins-det].

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11. K. Piscicchia *et al.*, Beyond Quantum Mechanics? Hunting the 'Impossible' Atoms - Pauli Exclusion Principle Violation and Spontaneous Collapse of the Wave Function at Test, Acta Phys.Polon. B46 (2015) 1, 147-152, DOI: 10.5506/APhysPolB.46.147.