VIP

S. Bartalucci, M. Bazzi (Art. 23), A. Clozza, C. Curceanu (Resp. Naz.),
C. Guaraldo, M. Iliescu (Art. 23), F. Lucibello (Tecn.),
S. Okada (Art. 23), D. Pietreanu (Bors. UE), A. Rizzo (Bors. PhD),
A. Scordo (Ass. Ric), D. Sirghi (Art. 23), F. Sirghi (Bors. UE), O. Vazquez Doce (Bors. UE)

1 The VIP scientific case and the experimental method

The Pauli Exclusion Principle (PEP), which 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, is a consequence of the spin-statistics connection. 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 seems appropriate to carry out precise tests of the PEP validity and, indeed, mainly in the last 15-20 years, several experiments have been performed to search for possible small violations. Moreover, many (if not all) of these experiments are using methods which are not obeying to the so-called Messiah-Greenberg superselection rule. 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 6 Institutions of 7 countries, has the goal to improve the limit on the probability of the violation of the PEP for electrons, (P $<$ 1.7 x 10^{-26} established by E. Ramberg e G. A. Snow: *Experimental limit on a small violation of the Pauli principle*, Phys. Lett. **B 238** (1990) 438) by three-four orders of magnitude (P $<10^{-29\div-30}$), exploring a region where new theories might allow for a possible 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 one of the new electrons is captured by a copper atom and cascades down to the 1s state already filled by two electrons with opposite spins. The energy of this 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 "fresh" 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.

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

2 The VIP experimental setups

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

The CCDs were 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 about 165 K by the use of a cryogenic system. The setup was surrounded by layers of copper

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

and lead (as seen in the picture) to shield the setup against the residual background present inside the LNGS laboratory, see Fig. 1.

A schematic drawing of the VIP setup is shown in Fig. 2.

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. Since 2011 we are preparing a new version of the setup - see below - in order to gain a factor 100 in the probability of violation.

3 Activities in 2012

3.1 Present VIP limit on PEP violation

Until summer 2010 the VIP experiment was in data taking, alternating periods of "signal" (I=40 A) with periods without signal (I=0 A). Data analyses were performed (energy calibration, sum of spectra, subtraction of background) and the probability of violation of PEP for electrons obtained (upper limit):

$$\frac{\beta^2}{2} < 4.7 \times 10^{-29} \quad (1)$$

We are attempting an interpretation of our results in the framework of quon-theory, 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

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

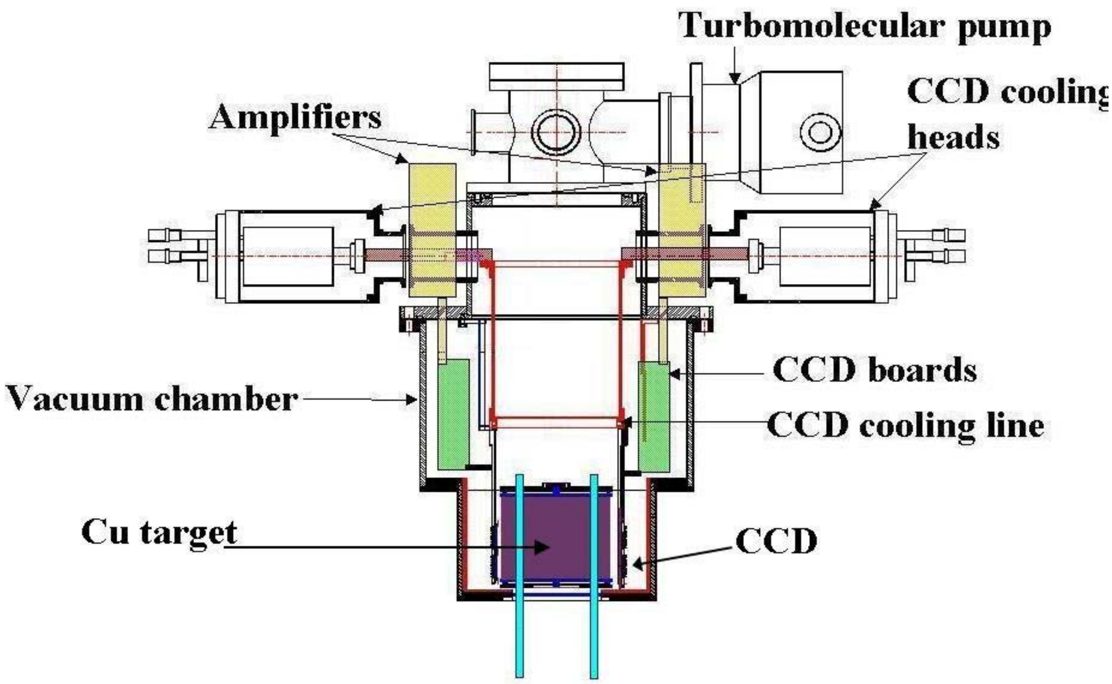

Figure 2: *The VIP setup. All elements of the setup are identified in the figure.*

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

$$\frac{1+q}{2} < 4.7 \times 10^{-29} \tag{3}$$

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, presented in our published papers (see list at the end).

3.2 VIP2 - a new high sensitivity experiment

In order to achieve the 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 target, a new cryogenic system and use new detectors with timing capability and active veto system. As x-ray detectors we use SDDs which were employed in der SIDDHARTA experiment on kaonic atoms at the DAΦNE electron-positron collider of Laboratori Nazionali di Frascati. SDDs have an even better energy resolution than CCDs but additionally provide timing capability which allow to use anti-coincidence operation with scintillators and therefore active shielding. The VIP2 system will provide:

1. signal increase with a more compact system with higher acceptance and higher current flow 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 higher than ∼120.

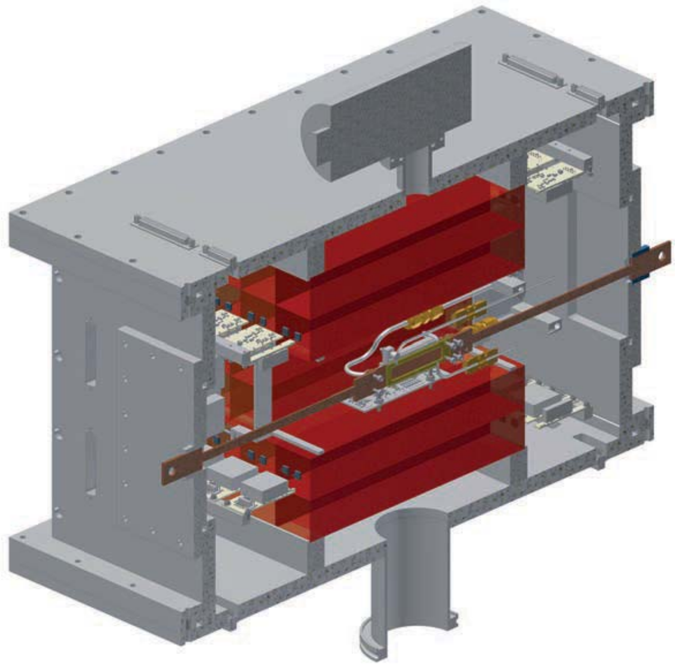

Figure 3: An artist view of the VIP2 experimental setup. In the middle the copper conductor and the x-ray detectors are installed. Plastic scintillators with solid state photodetector readout acting as active sgielding are surrounding the inner part.

Figures 3 shows the main elements for the proposed setup in the VIP2 experiment. The copper strip target is 30 mm long, 10 mm wide and is about 40μm thick, and is installed in the center of the setup. The copper strip is cooled at $\sim$90K by the use of an external cryogenic system using liquid argon as the cooling medium. The current connection lines made of copper wires with a cross-section area of 1.5 cm^2, allow a current flow of (at least) 100 A.

The current lines exhibit a temperature gradient from inside the vacuum chamber to the outside connectors of about 180 K. Monte Carlo simulations were performed to study the effect of the active shielding in various configurations of the setup and models of the background radiation. The background profiles measured at LNGS were used as input parameters in the simulations. As the veto counters, 2 pieces of 10 cm thick plastic scintillators are found to be optimal. During 2012 various elements of the setup were built and tested. Presently the setup is being assembled in Vienna SMI and Frascati laboratories for the final tests.

4 Activities in 2013

In 2013 we plan to finalize the construction of the VIP upgraded setup and install, debug and test at LNGS and start the data taking. We are, as well, considering to extend the scientific program towards a feasibility study of limits on parameters of 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.

Table 1: List of numerical values of the changes in VIP2 in comparison to the VIP features (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 implementation		$\sim$120

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. The support from the HadronPhysics FP6, HadronPhysics2 and HadronPhysics3 FP7 and from EU COST 1006 Action projects is acknowledged.

5 List of Conference Talks by LNF Authors in Year 2012

Include a list of conference talks by LNF authors.

1. A. Rizzo, "A new experimental upper limit on λ paramater", Quantum Malta 2012: Fundamental Problems in Quantum Physics, 24-27 April 2012, La Valletta, Malta.
2. A. Rizzo, "A new experimental upper limit on λ paramater", Open Problems in Quantum Mechanics, 20-22 June 2012, LNF, Frascati, Italy.
3. C. Curceanu, "A glimpse into the Pandora Box of quantum mechanics: the Pauli Exclusion principle violation and the spontaneous collapse models put at test",QFRF6, 11-14 June 2012 Vaxjo, Sweden.
4. C. Curceanu, "A glimpse into the Pandora Box of quantum mechanics: the Pauli Exclusion principle violation and the spontaneous collapse models", Fundamental problems in Quantum Physics, 24-27 April 2012, La Valletta, Malta.

6 Publications

References

1. C. Curceanu (Petrascu) *et al.* (The VIP Collaboration), A glimpse into the Pandora box of the quantum mechanics: The VIP exclusion principle violation and spontaneous collapse models put at test, AIP Conf. Proc., 136-145 (2012).

2. C. Curceanu (Petrascu) *et al.* (The VIP Collaboration), Experimental tests of Quantum Mechanics: from Pauli Exclusion Principle Violation to spontaneous collapse models, Journal of Physics, Conference Series, Vol. 361 (2012).

3. C. Curceanu (Petrascu) *et al.* (The VIP Collaboration), Experimental tests of quantum mechanics: Pauli Exclusion Principle Violation and spontaneous collapse models, AIP Conference Proceedings, 1424, 397-406 (2012).

4. C. Curceanu, J.D. Gillaspy, R.D. Hilborn, Resouce Letter SS-1: The Spin Statistics Connection, American Journal of Physics, Vol. 80, Issue 7, 561-577 (2012).

5. J. Marton *et al.* (The VIP Collaboration), Testing the Pauli Exclusion Principle for Electrons, arXiv:1302.7218 [nucl-ex].

6. S. Donadi *et al.*, Are Collapse Models Testable via Flavor Oscillations?, arXiv:1207.6000 [quant-ph].

7. S. Donadi *et al.*, The effect of spontaneous collapses on neutrino oscillations, arXiv:1207.5997 [quant-ph].

8. C. B. Hiesmayr *et al.*, Revealing Bell's Nonlocality for Unstable Systems in High Energy Physics, Eur.Phys.J. C72 (2012) 1856.