THE VIP EXPERIMENT

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on behalf on the VIP Collaboration

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Abstract The Pauli Exclusion Principle (PEP) is a basic principle of Quantum Mechanics, and its validity has never been seriously challenged. However, given its importance, it is very important to check it as thoroughly as possible. The recently approved VIP (VIolation of Pauli Exclusion Principle) experiment represents an improved version of the Ramberg and Snow experiment (Ramberg and Snow, Phys. Lett. B238 (1990) 438). VIP shall be performed at the Gran Sasso underground laboratories (Italy), and aims to test the Pauli Exclusion Principle for electrons with unprecedented accuracy. It uses an apparatus with CCDs (Charge Coupled Device) as detectors of X rays - looking for PEP violating transitions in Copper: transitions from the 2p level to 1s with the 1s already occupied by 2 electrons. The characteristic of such transition is its energy - displaced with respect to the normal 2p→1s one by about 300 eV. VIP will bring the limit on the probability that PEP is violated by electrons to 10^{-30}, four orders of magnitude better than the present limit, exploring so a region where new theories might allow for a possible PEP violation.

Key words: Quantum Mechanics, Pauli Exclusion Principle, anomalous atomic transitions measurements

1. THE VIP SCIENTIFIC CASE

The Pauli Exclusion Principle (PEP) represents one of the **fundamental principles** of the modern physics and all our comprehension of the surrounding matter is based on it. Even if today there are no compelling reasons to doubt its validity, it still spurs a lively debate on its limits, as testified by the abundant contributions found in the literature and in topical conferences [1].

Before discussing the present status of the Pauli Exclusion Principle, let's briefly summarize PEP in non-relativistic quantum mechanics (following Mandl [2]).

Consider, for example, the helium atom Hamiltonian:

$$H_0\left(\mathbf{r}_1,\mathbf{r}_2\right)=\sum_{i=1,2}\left(-\frac{\hbar^2}{2m}\nabla_i^2-\frac{2e^2}{4\pi\varepsilon_0 r_i}\right)+\frac{e^2}{4\pi\varepsilon_0 r_{12}} \qquad (1)$$

which is symmetric with respect to the coordinate exchange of the two electrons. Requiring the Hamiltonian to be symmetric corresponds to assume that the two electrons are indistinguishable. Even in the case of an approximate, non-relativistic, Hamiltonian, the indistinguishable character of the two electrons tells us the fact that the exact Hamiltonian should contain the same type of symmetry. For example, if one includes the spin **s,** the Hamiltonian should be a function of the type $H_0\left(\mathbf{r}_1,\mathbf{r}_2;\mathbf{s}_1,\mathbf{s}_2\right)$ and should continue to be symmetric with respect to the 1-2 exchange operation.

Generally, considering the Hamiltonian of a system of *N* electrons, the indistinguishability constrains us to write it such as to be invariant to the any-two *i,j* electron exchange operation:

$$H\left(1,\ldots,i,\ldots,j,\ldots,N\right)=H\left(1,\ldots,j,\ldots,i,\ldots,N\right) \qquad (2)$$

The symmetry of the Hamiltonian induces a degeneration of the eigenvalues, namely:

$$H\left(1,2\right)\psi(1,2)=H\left(1,2\right)\psi(2,1)=E\psi(1,2)=E\psi(2,1) \quad (3)$$

One can therefore define the following linear combinations:

$$\psi(1,2)\pm\psi(2,1) \qquad (4)$$

which are the eigenfunctions for the same eigenvalue having a defined parity (±1) with respect to the 1-2 permutation.

Furthermore, one can deduce that the time evolution dictated by the Schroedinger equation:

$$i\hbar\frac{\partial}{\partial t}\psi(1,2,t)=H(1,2)\psi(1,2,t) \qquad (5)$$

cannot modify the symmetry of the wave-functions (the Hamiltonian commutes with the permutations).

The symmetrization postulate states that the only acceptable ("physical") linear combinations are either completely symmetric or antisymmetric, condition which adds to the symmetry of the Hamiltonian (which is dictated by the indistinguishability of particles). In 1940 W. Pauli demonstrated that a relativistic field theory for identical particles can be built only if the integer-spin particles do have symmetric wave functions while the half-integer spin ones have antisymmetric wave functions [3]. At this point, it is important to notice that in the case of non-interacting particles one can write the global wave function in terms of superposition of the single-particle ones.

For example, in the case of 2 particles of half-integer spin, one can write the wave-function as:

$$\Psi\left(1,2\right)=\psi_a(1)\psi_b(2)-\psi_b(1)\psi_a(2) \tag{6}$$

where *a, b* are the spin indices. If the particle spins are equal, then:

$$\Psi\left(1,2\right)=\psi_a(1)\psi_a(2)-\psi_a(1)\psi_a(2)=0 \tag{7}$$

the wave function is identically zero, i.e. unphysical state, meaning *that two particles with half-integer spin cannot be in the same quantum state: in this form they symmetrization principle is known as the Pauli Exclusion Principle.*

As one can check, in the exclusion principle there are actually *two assumptions*: particles of the same "type" are indistinguishable, and the global wave function is antisymmetric. Moreover, it contains a relativistic element, namely the particle spin coordinate.

It is worthy to note that Dirac [4] and Pauli [5] considered in depth the consequences of this principle and concluded that the electronic transitions towards a free shell of an atom could be forbidden by the symmetrization alone, independently of the exclusion principle validity, because such transitions would modify the symmetry of the wave function.

Moving now to relativistic quantum mechanics, it is rather easy to demonstrate that the second quantization of the Dirac's equation retains physical meaning only if the corresponding fields do anticommute [6], while the Klein-Gordon equation is valid for commuting fields [6]. It is however less easy to prove that, generally, a quantum theory is coherent only if the half-integer spin particles are described by anticommutators while the integer spin ones by commutators.

As previously mentioned, Pauli gave a first rigorous demonstration of this link between spin and statistics in 1940 in a classic paper [3]. In the following years, other physicists investigated the link between spin and statistics, and, one of the clearest formulations is the one of Lüders and Zumino [7].

The Pauli principle plays a fundamental role in the explanation of several physical processes, ranging from the atomic periodic table, to the theory of electric conduction in metals, to the degeneracy pressure which makes both white dwarfs and neutron stars stable.

Although the principle is spectacularly confirmed by the number and the accuracy of its predictions, it is still possible to speculate that it is only an approximation of a more fundamental law, and that there may be tiny violations.

It is not trivial to build a theory which consistently incorporates a violation of the Pauli Exclusion Principle, and it is surely beyong the scope of this introduction to account for all the more or less successful attempts. Just to give a flavour of such a theory, we present a simple case, namely the Ignatiev and Kuzmin (IK) model [8]. In this model, creation and destruction operators connect 3 states, the vacuum state $|0\rangle$, the single occupancy state $|1\rangle$ and a nonstandard double occupancy state $|2\rangle$, through the following relations:

$$a^+|0\rangle = |1\rangle; \qquad a|0\rangle = 0;$$
$$a^+|1\rangle = \beta|2\rangle; \quad a|1\rangle = |0\rangle; \qquad (8)$$
$$a^+|2\rangle = 0; \qquad a|2\rangle = \beta|1\rangle;$$

from which the algebra of the operators is obtained as:

$$a^2a^+ + \beta^2a^+a^2 = \beta^2a + H.C.$$
$$a^2a^+ + \beta^4a^+a^2 = \beta^2aa^+a + H.C. \qquad (9)$$
$$a^3 = (a^+)^3 = 0$$

(this represents a particular case of the trilinear algebra introduced by Green [9]). Successively, one introduces the particles number operator N, which obeys at the well known commutation relations:

$$[N,a] = -a; \quad [N,a^+] = a^+; \qquad (10)$$

and one finds that this operator can be expressed as a function of the creation and destruction operators as:

$$N = \frac{1}{1-\beta^2+\beta^4}\left[\left(-1+2\beta^2\right)a^+a + \left(-2+\beta^2\right)aa^+ + \left(2-\beta^2\right)I\right] \qquad (11)$$

(I being the identity operator). The IK paper concludes with a detailed exam of a perturbed Hamiltonian which includes an explicit violation of the exclusion principle and from here one calculates a transition probability per unit time $W(|1\rangle \to |2\rangle)$, which obviously depends of the violation parameter β.

Applying this model to the electrons one can interpret the states $|1\rangle$ and $|2\rangle$ as states occupied by one or more electrons. Experimentally this means that anomalous atoms could exist (atoms with an anomalous filling of the electron shells) and/or that instability conditions could emerge (an electron can pass from $|1\rangle$ to $|2\rangle$ through the emission of an X-ray). This is the very reason which motivated past searches for anomalous X-rays and for the so-called non-Paulian atoms.

The IK theory introduces, in a simple and seemingly natural way, the violation of the Pauli principle. Many objections can be raised against this theory, as those formulated in a paper by Amado and Primakoff [10] who state that:

- if the Hamiltonian is symmetric, then transitions to a state with a different permutation symmetry are not allowed;
- if the electrons can have an antisymmetric component, then, due to the indistinguishability of electrons, all electrons should be "a bit" antisymmetric. On the other hand, this "bit" should not be necessarily

small, and then one can wonder why, in reality, should then be so "extremely small";

- if different symmetry states do exist, than the components having different symmetry should be degenerate in energy and this close to a "miracle", since it is exceedingly unlikely that such a coincidence takes place;
- a way out could be to give up to the perfect indistinguishability and to assume that particles very similar, but not identical, do exist. But – if all electrons could be, even very slightly different, the exclusion principle would not hold in many cases and this is in contrast with the experimental evidence;
- another possibility is that only some electrons are different, but in such a case the radiative transitions to the K shell should have occurred long time ago, and then it is not very likely that one can presently observe X rays from this process. Moreover, this hypothesis would give rise to an increase (not observed) of the experimental cross-section in the e^+e^- colliders.

Apart of the Amado and Primakoff observations, there are some more technical ones, as the one of Biedenharn, Truini and van Dam (BTvD), who directly criticize the IK model [11]. BTvD introduce two states, called $|e\rangle$ and $|\mu\rangle$, and creation and destruction operators which act on the tensorial product of the states according to the relations:

$$\begin{aligned} b^+|0\rangle &= \cos\theta_B|e\rangle + \sin\theta_B|\mu\rangle = |1\rangle \\ b^+|1\rangle &= 2\sin\theta_B\cos\theta_B|e\rangle|\mu\rangle = \sin 2\theta_B|2\rangle \end{aligned} \tag{12}$$

If now one replaces $\beta = \sin 2\theta_B$, same relations as the IK ones are obtained, meaning that the IK model is nothing else than a formulation of a theory which contains two similar fermions which mix, but remain different one from the other.

These, however, are very subtle arguments and it is easy to get wrong answers: Okun, in one of his famous articles [12], notes that the BTvD argument is not valid, unless the states are degenerate in mass, and such states are excluded by experiments. Unfortunately the IK model leads to negative probability states as remarked by Govorkov [13] and this destroys quite a bit its credibility.

It is clear that part of the interest towards these very important fundamental principles is due to their evasiveness, thing which is well expressed in a small note on American Journal of Physics in 1994 [14], in which D. E. Neuenschwander asked if there were progress towards an elementary explanation of the spin-statistics theorem, which even R. Feynman was unable to give.

Greenberg and Mohapatra [15] in their work laid the basis of one of the recent experimental checks of the exclusion principle for electrons [16], which, in turn, has inspired the VIP proposal. In their work they put forward a hypothesis concerning the possible origin of an apparent Pauli exclusion principle violation: namely the possible existence of compactified extra-dimensions. In this case, the Pauli principle would remain perfectly valid in a space with more than 3+1 space-time dimensions.

Obviously, the indistinguishability and the symmetrization (or antisymmetrization) of the wave-function should be checked independently for each particle, and accurate tests were or are done for nucleons and photons, apart from electrons (the papers [17-29] represent a partial list of the experimental tests performed in recent years).

The VIP experiment aims to improve the current limit on the violation of the Pauli principle for electrons, ($P<1.7 \times 10^{-26}$), reported in [16], by four orders of magnitude ($P< 10^{-30}$), exploring a region where new theories [6,15] might allow for a possible PEP violation.

2. EXPERIMENTAL METHOD

Experimental tests of the Pauli exclusion principle for electrons are done, basically, in two different ways:

1. the search for the so-called “non-Paulian” atoms, as the paronic helium for example, characterized by an electron in the fundamental level and the other in an excited one, such as the spin and the space components of the wave functions are both antisymmetric, resulting in a global state of the $1s2s^1S_0$ for which the total wave function is symmetric – violation of the symmetrization principle [21];
2. the search for “anomalous” X-ray transitions, i.e. electron transitions to states already occupied by the maximum allowed number of electrons compatible with the Pauli exclusion principle.

It is this second method, already used by Ramberg and Snow [16], and derived from the original experiment of Goldhaber and Goldhaber [30], which will be used in VIP.

The basic idea is to introduce “new” (fresh) electrons in a copper bar (new in the sense that the already existing ones in the copper bar had already all the time to perform the allowed and “prohibited” transitions) and measure the K-series ($2p\rightarrow1s$) X-ray transitions in which the 1s level is already occupied by 2 electrons. Such transitions, obviously, would only be possible if the Pauli principle is violated, see Fig. 1.

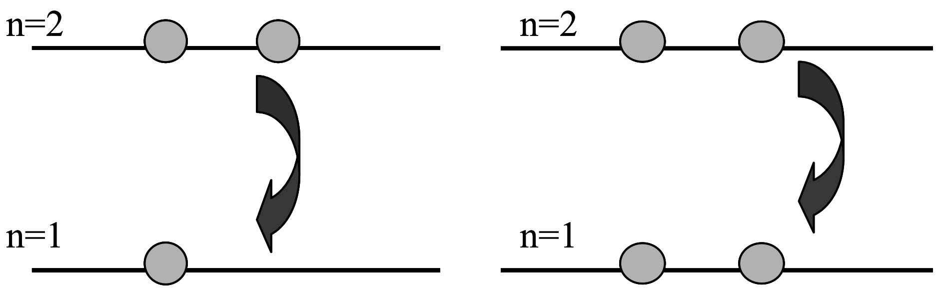

Fig. [1]. –

$2p\rightarrow1s$ allowed transition $2p\rightarrow1s$ transitions violating the Pauli principle

The “anomalous” transitions are detected by their energy shift because instead of the normal 8.05 keV energy of the 2p→1s transition in Copper, one gets a value closer to the one corresponding to a (Z-1) atom (7.5 keV in this case) [31], which can be readily measured (a high resolution X-ray detector).

Taking into account the integrated circulated current, the geometry and the material characteristics, the result of the Ramberg and Snow measurement, in terms of the β-parameter (see Section 1), yielded an upper limit for the probability of the Pauli principle violation of:

$$\beta^2/2 < 1.7 \times 10^{-26}$$

3. PRELIMINARY RESULTS OBTAINED WITH A TEST SETUP

A feasibility measurement, applying the same method of Ramberg and Snow, was performed by us in 1998 for a period of three months, in the basement of the Neuchâtel laboratory [32]. The setup used 3 CCD’s (Charge Coupled Device) as X-ray detectors, with an energy resolution of 400-500 eV FWHM, already about 3 times better that the Ramberg and Snow setup.

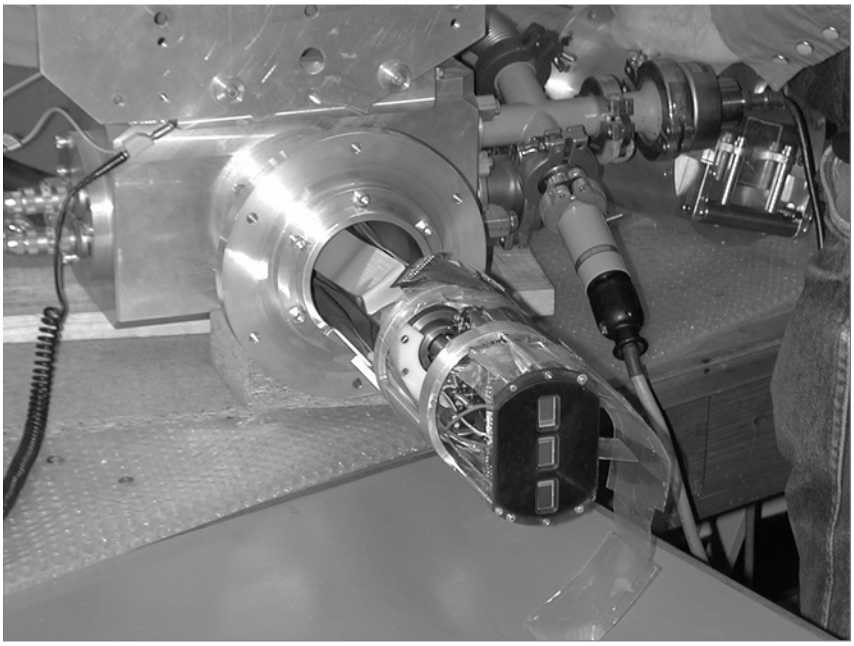

Fig.[4]. -

The test setup used at Neuchatel – detail of the CCD detectors.

As an example, the measured spectra for one CCD are shown in Fig. 5.

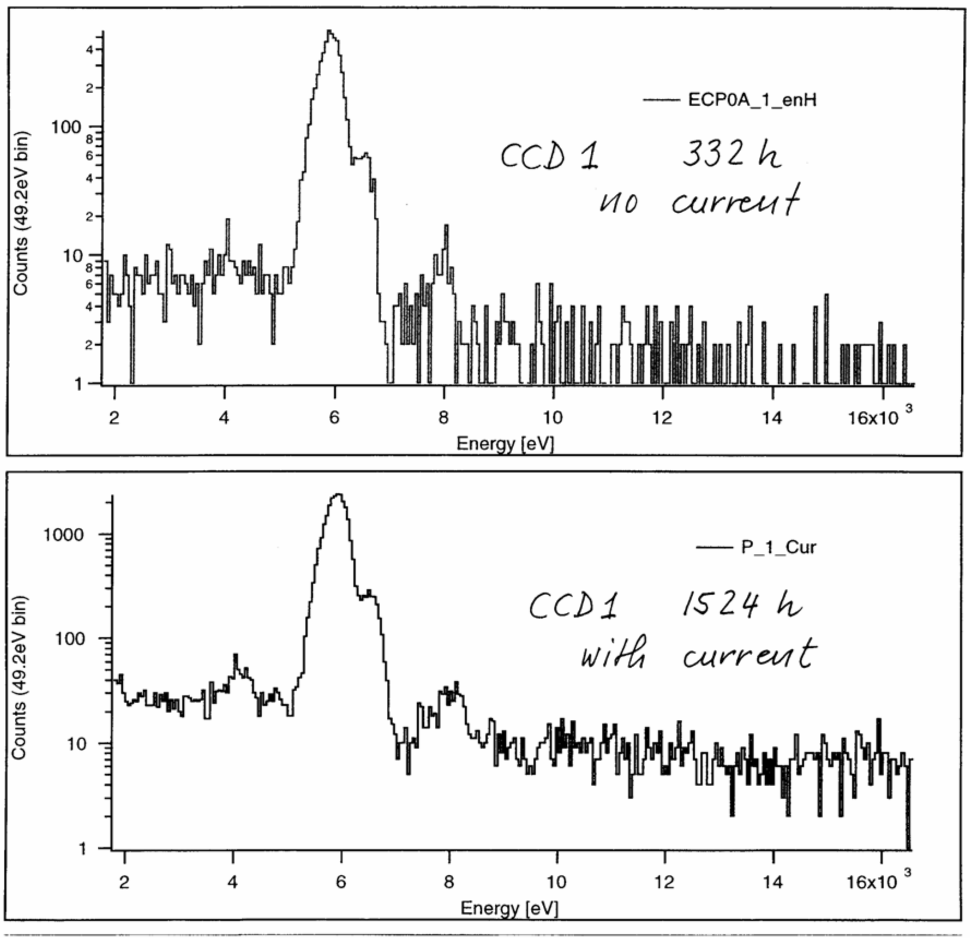

Fig. [5]. –

The measured spectra with the test setup at Neuchatel.

With the improved detector resolution and geometry, taking into account the integrated circulated current, the geometry and the material characteristics, an upper limit of:

$$\beta^2/2 < 0.95 \times 10^{-27}$$

was obtained, an order of magnitude better than the Ramberg and Snow measurement.

4. THE VIP EXPERIMENT

The VIP experiment has the goal to push the limit on the Pauli exclusion principle violation for electrons to 10^{-30}. Such a value is of particular interest in the framework of those theories which are anticipating violations of this order. VIP is a Collaboration among four Institutions out of three countries (LNF-INFN, and INFN Trieste Italy; SMI-Vienna, Austria; IFIN-HH, Bucharest, Romania).

4.1 The VIP setup

The VIP setup is going to be built starting from the DEAR one, which was successfully used to measure other exotic X-ray transitions (kaonic nitrogen and hydrogen ones at the DAΦNE accelerator [33, 34, 35]).

The most important modification to the setup is the replacement of the plastic vessel, which contained the target gas in the DEAR experiment, with a copper conductor, which must be able to carry a large current close to the surface (fig. 8). A current of 50 A will be circulated in the copper target.

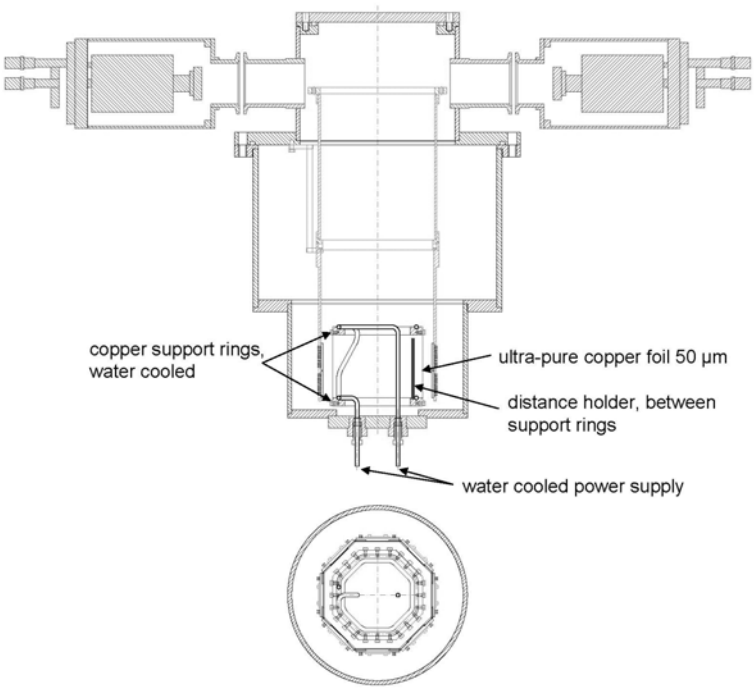

Fig. [8] –

The VIP setup.

This solution should provide a uniform distribution of the surface current and, at the same time, a higher surface current density with respect to the copper bar “à la Ramberg and Snow”, thus optimizing the acceptance and the detection efficiency for the X-rays.

4.2 VIP expected performances

The present VIP setup improves on the Neuchâtel setup as follows:

- 16 CCD-55 with a sensitive are ~ 30 times larger than the Neuchâtel test and ~ 18 times larger than the RS experiment;
- an energy resolution of the currently used CCD-55’s a factor 2 to 3 better than the CCD-05’s used at Neuchâtel and approximately 10 times better than the RS setup;
- at least one year data taking time (with circulating current) – giving a factor ~ 5.7 more than Neuchâtel test, and approximately 5 times the RS experiment;
- a measurement time of one year for the background (no-current) – representing a factor ~ 25 more than the Neuchâtel test and about 5 times longer than the RS experiment;
- a 50 A circulating current – a factor about 5 more than Neuchâtel; we also hope to improve on the RS experiment with a setup that keeps the current as close to the conductor surface as possible;
- a background reduced by a factor ~ 100 at Gran Sasso, with respect to Neuchâtel and RS (Fermilab);

These combined factors allow VIP to obtain an upper limit for the Pauli principle violation for electrons of:

$$\beta^2/2 < 10^{-30}$$

4.3 Two CCD test setup and measurement of background at LNGS

The goal of the VIP experiment [1] is to push the limit on the probability of the violation of the Pauli Exclusion Principle (PEP) for electrons by four orders of magnitude with respect to the presently published value of $\beta^2/2 < 1.7 \times 10^{-26}$ [16]. The 4 orders of magnitude to be achieved ($\beta^2/2 < 10^{-30}$) should arise both from detector design considerations and from a substantial reduction of the background.

A 2 CCD test setup was built with the goal to measure the background at LNGS, to estimate the reduction factor with respect to ground-level rates (as performed for instance in Neuchâtel).

In the period November 2004 – April 2005 an intense activity was dedicated to measurements of the background in the DEAR Laboratory at Frascati and at the

LNGS Laboratories. A 2 CCD test setup was used, having the same type of CCDs (CCD55) as those used in the VIP setup. Moreover, the materials of the setup are of the same quality and purity as those from the setup.

The calibration measurement was done with a Fe source, and the resulting spectrum, calibrated in energy, is shown in Fig. 4. A second calibration measurement was performed at the end of the measurements in the laboratory, and the result was the same as the one reported in Fig. 4, checking in this way the stability of the energy calibration.The energy resolution was of 180 eV (FWHM) at about 6 keV.

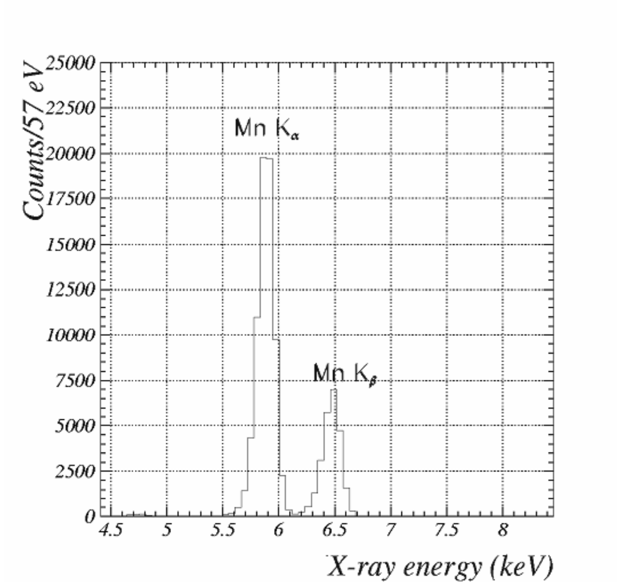

Fig. [9]. –

Energy calibration – measurement with an Iron source performed in the DEAR laboratory.

The list of the background measurements with a 2 CCD test setup were performed in the DEAR laboratory at Frascati and at the LNGS laboratories, without and with shielding is the following:

- background measurement done in the DEAR laboratory, without shielding, which lasted 65 hours;
- background measurement done in the DEAR laboratory, with shielding, which lasted 325 hours. The shielding was composed of an external layer of Lead (10 cm thick) and an internal layer of Copper (5 cm). The setup was enclosed in a plastic housing flushed with nitrogen, in order to remove possible Radon contamination;
- background measurement done with setup installed at LNGS, without shielding, which lasted 60 hours;
- background measurement done with setup installed at LNGS, with a preliminary shielding, which lasted 832 hours. The shielding was done in an

external layer of lead and an internal one of copper, 5 cm thickness each. In the Fig. 10 the 2 CDD test setup with shielding as installed at LNGS, is shown.

Fig. [10]. –

The 2 CCD test setup with shielding taking data at LNGS.

A comparison between the normalized spectra such obtained is realized in Fig. 11.

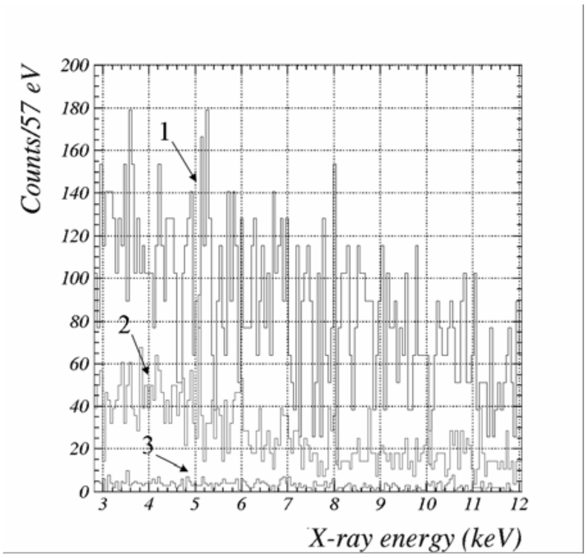

Fig. [11]. –

Comparison between normalized background spectra obtained with the 2 CCD setup: in (1) the result obtained in the laboratory without shielding; in (2) the results obtained in the laboratory with shielding; in (3) the results obtained with a preliminary shielding at LNGS.

By using a preliminary shielding at LNGS we have obtained:

- a background reduction factor of about 6.3 with respect to LNGS without shielding;
- a background reduction factor of about 30 with respect to laboratory without shielding;
- a background reduction factor of about 45 with respect to Neuchatel measurement.

5. SUMMARY AND CONCLUSIONS

A background reduction factor of about 50 was obtained at LNGS with respect to the Neuchâtel measurement (as reported in Section 4), by using a preliminary shielding.

An increase of the background reduction factor to the value of 100 or more is feasible, by:

- design of a special VIP shielding geometry, which better covers all the solid angle;
- use of specially treated shielding materials (lead and copper);
- flushing with nitrogen

The VIP experiment is going to start data taking in 2005 and will run for two years with the goal of reaching the 10^{-30} limit on the PEP violation parameter for electrons, exploring so a region where new theories might allow for a possible PEP violation.

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