Experimental search for the "impossible atoms" Pauli Exclusion Principle violation and spontaneous collapse of the wave function at test

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Abstract. Many experiments investigated the possible violation of the Pauli Exclusion Principle (PEP) since its discovery in 1925. The VIP(Violation of the Pauli Principle) experiment tested the PEP by measuring the probability for an external electron to be captured and undergo a 2p to 1s transition during its cascading process, with the 1s state already occupied by two electrons. This transition is forbidden by the PEP. The VIP experiment resulted in an upper limit for the probability of PEP violation of 4.7×10^{-29}. Currently a setup for the follow-up experiment VIP2 is under preparation. The goal of this experiment is to improve the upper limit for the violation of the PEP by two orders of magnitude, by using new X-ray detectors and by implementing an active shielding. We then present the idea of using an analogous experimental technique to search for X rays as a signature of the spontaneous collapse of the wave function, predicted by the continuous spontaneous localization theories, and discuss some very encouraging preliminary results.

1. Introduction

Formulated by Wolfgang Pauli in 1925 [1], the Pauli Exclusion Principle (PEP) is one of the building blocks of quantum mechanics. It is the foundation for our understanding of nuclear physics, particle physics, condensed-matter physics, and astrophysics where many-fermion systems are concerned. By far the principle does not have an intuitive explanation for its physical cause, and there is possibility that high precision experiment may discover small violation that could reveal more fundamental principles. However the experimental test is difficult because there has been no well-established parameter that can account for PEP violation quantitatively in a theory.

In the reviews given by Greenberg and Mohapatra [2, 3], they surveyed over the searches for a phenomenology framework for possible small violation of the PEP, and then pointed out that no satisfactory solution could be found to be consistent within a local field theory. However, they argued that following the parameterization proposed by Ignatiev and Kuzmin (IK) [4], in an extended model of a single fermion-like oscillator which allows double occupancy with a small amplitude of β, one can discuss about the phenomenology of a small violation of the PEP with a parameter quantitatively derivable from experiments.

The first precision measurement done by Ramberg and Snow [5] follows a method Greenberg and Mohapatra [6] proposed after they extended the IK model. The method first used by Goldhaber and Scharff-Goldhaber [7] back in 1948, was initially intended to check if the beta rays from beta decay are identical to ordinary electrons. Their idea was that, if not identical to electrons, the beta rays absorbed by a block of metal (in this case lead) will neglect all the electrons occupying the atomic states and deexcite via the cascade process. The $2p$-$1s$ transition will have a different energy with respect to the normal $2p$ - $1s$ transition, due to the shielding effect of an additional electron in the ground state [11]. Based on the non-existence of the anomalous X-rays, they first concluded the equivalence of beta ray to electron, and, more interestingly, they later pointed out the experiment can be interpreted as a test for PEP. A quantitative evaluation based on the result of the experiment was done by Greenberg [3], who deduced explicitly that the possibility that the PEP can be violated is less than 0.03.

The idea of introducing external "fresh" electrons to the target system as applied by this pioneering experiment and the Ramberg-Snow experiment is crucial in the method of testing the PEP for electrons. Without the "fresh" electrons, two experiments in the 1970s [8, 9] looked for prohibited X-rays or γ rays from stable atomic or nucleus systems, and argued the null results served as tests for the PEP violation. However this type of measurement does not validate to be a test, because it has assumed that the transitions between different permutation group could occur. Such assumption violates in the first place the superselection rule separating states in different presentations of the symmetric group [10]. On the other hand, external electrons that had no interaction with the target system not only make source of electrons in large population possible, they are also the pre-requisite that small violation of the PEP can be discussed in the framework of quantum mechanics as Greenberg proposed [3]. Because the newly captured electron and the copper atom have the possiblility of forming a "mixed" symmetry state that is highly excited, anomalous X-rays can be observed. To represent the probability of a small violation of the PEP in the absence of a field theory, Ramberg and Snow used the β parameter introduced first in the IK model. For a random pair of electrons, $1 - \frac{1}{2}\beta^2$ is the possibility of the pair in the normal antisymmetric state, and $\frac{1}{2}\beta^2$ the probability in the anomalous symmetric state. In the IK model, β is explicitly defined with the zero, one, and two particle states of $|0\rangle$, $|1\rangle$, and $|2\rangle$, together with the creation operator $a^\dagger$ and the annihilation operator a as :

$$a^\dagger|0\rangle = |1\rangle, a^\dagger|1\rangle = \beta\,|2\rangle, a^\dagger|2\rangle = 0. \quad a\,|0\rangle = 0, a\,|1\rangle = |0\rangle, a\,|2\rangle = \beta\,|1\rangle; \qquad (1)$$

Following the IK model, Greenberg and collaborators constructed the "quon" algebra [16]

with q parameter:

$$a_k a_l^\dagger - q \, a_l^\dagger a_k = \delta_{kl}, \tag{2}$$

which can be understood as the average of the Bose and Fermi commutation relations:

$$\frac{1+q}{2}[a_k, a_l^\dagger]_- + \frac{1-q}{2}[a_k, a_l^\dagger]_+ = \delta_{kl}, \tag{3}$$

and the β parameter can be written in terms of the q parameter as:

$$\frac{1}{2}\,\beta^2 = \frac{1}{2}\,(1+q). \tag{4}$$

Although still having open questions to solve, the "quon" theory is by far the best attempt to violate by a small amount the Fermi and the Bose statistics. However, for a direct comparison of the experimental results, the VIP experiment used and will use the same notation of β^2 by Ramberg and Snow.

In next section, we describe the experimental method used by VIP experiment, and show the improvements in the sensitivity achieved with respect to the past experiments. Afterwards we introduce our follow-up experiment VIP2 and its progress in the ongoing preparation.

2. VIP experimental method

With the same idea of searching for anomalous transition X-rays, Ramberg and Snow improved drastically the sensitivity by changing the source of electrons from beta decay to constant electric current. Performed at the ground floor of the Muon building at Fermilab, they used a proportional tube counter as the X-ray detector with a resolution of 1 keV at 8 keV, and a large array of plastic scintillators to veto possible signals from charged cosmic rays. A thin strip copper as target was connected to a 50 A power supply. By comparing the X-ray spectra from measurements with and without power supply, the excess of events in the forbiden transition energy region when current is supplied, will be due to the violation of the PEP.
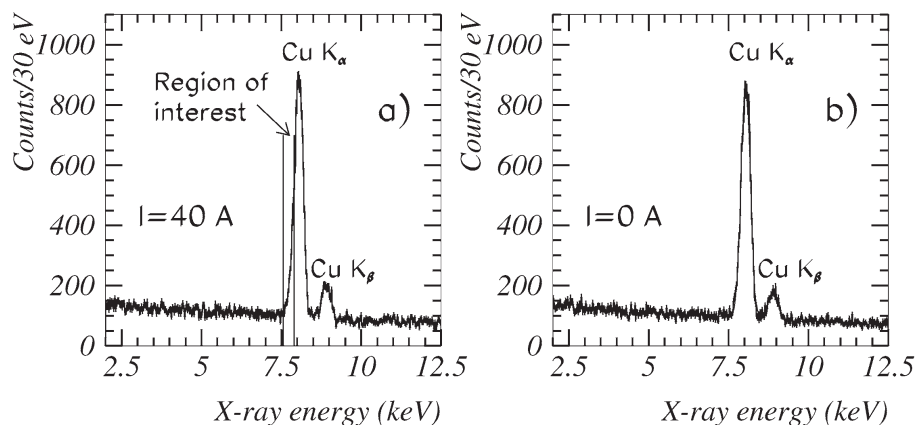

Figure 1. Energy spectra for the VIP experiment [12] : (a) with 40 A current, (b) without current, from part of the data set. Normal K transitions of Cu present are background, and they are due to excitation of target by cosmic rays and environmental radiations.

Table 1. Limits of the Pauli violation probability for electrons from recent high precision experiments:

Experiment	Target	Upper limit of $\beta^2/2$	reference
Ramberg-Snow	Copper	1.7×10^{-26}	[5]
S.R. Elliott et al.	Lead	1.5×10^{-27}	[14]
VIP(2006)	Copper	4.5×10^{-28}	[12]
VIP(2012)	Copper	4.7×10^{-29}	[13]
VIP2(goal)	Copper	$\times 10^{-31}$	[15]

2.1. VIP experiment and results

The VIP experiment followed the method of the Ramberg-Snow experiment, and used the same definition of the parameter $\frac{1}{2}\beta^2$ to represent the violation to the PEP for a direct comparison of the experimental results. The improvement in sensitivity was achieved firstly due to the site of the experiment at the underground laboratory in Laboratori Nazionali del Gran Sasso (LNGS), which has the advantage of the excellent shielding against cosmic rays [12]. The other reason is the use of Charge Coupled Device (CCD) as the X-ray detector which had a typical resolution of 320 eV at 8 keV, that increased the precision in the definition of the region of interest to search for anomalous X-rays.

In Table 1, all the results from experiments using "fresh" electrons are listed, together with the goal of the planned VIP2 experiment at LNGS.
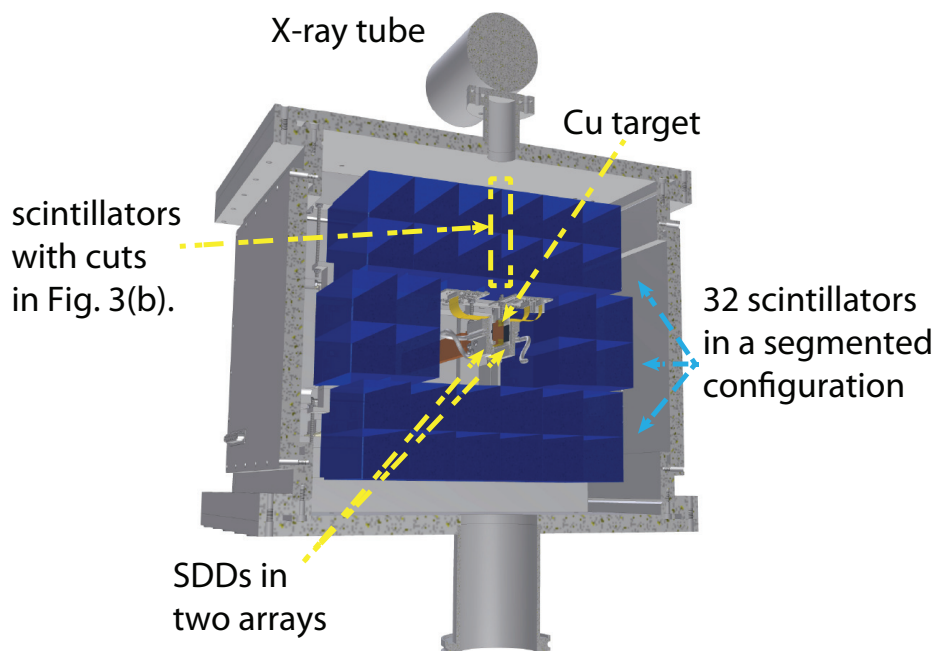
2.2. VIP2 experiment

Figure 2. An artist presentation for the cutaway view of the setup. Over 90% of the solid angle for the SDDs acceptance is covered by 32 plastic scintillators as active shielding. The timing capability of the SDDs will allow us to reduce most of the background of the Cu K-series X-rays induced by cosmic rays impinging on the target.

2.2.1. Design In the follow-up VIP2 experiment, we aim to improve the sensitivity of VIP experiment by two orders of magnitude [17]. A detailed list for the features that will contribute to the overall improvement is summarized in Table 2 [15]. The dominant factor of background reduction will come from the use of the Silicon Drift Detectors (SDDs) as the X-ray detector and to an active shielding with arrays of plastic scintillator as veto counters. Compared to the readout time of the order of seconds for CCD, the SDD has a charge collection time of less than one microsecond. This allows to use the time correlation between the X-ray events and the events at the veto counters, to exclude all the X-rays, including the K-series X-rays of Cu from the target excited by cosmic rays or by the environmental radiation, as the energy spectra in Fig. 1 show.

We plan to use six SDD detectors with a total active area of 6 cm^2 mounted close to the pure Cu target in the shape of a strip 3 cm in length. Surrounding the SDDs and readout electronics, as shown in Fig. 2, 32 pieces of plastic scintillators each with a dimension of 40 mm × 32 mm × 250 mm will be mounted in a segmented configuration, covering about 90% of the solid angle for the acceptance of SDDs. To readout the light output of each scintillator, we attach with optic cement solid-state Silicon Photo-Multipliers (SiPMs) directly to the scintillators. More information for the plastic scintillator and SiPM and its electronic board can be found in Ref. [15].

Table 2. The improvement factors for VIP2 in comparison to the features of VIP [15] :

Changes in VIP2	value VIP2 (VIP)	expected gain
acceptance	12 %	12
increase current	100 A (40 A)	> 2
reduced length	3 cm (8.8 cm)	1/3
total linear factor		8
energy resolution	170 eV (320 eV) @ 8 keV	4
reducecd 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 improvement		> 120

3. Future perspectives: tests of collapse models

We are presently considering the possibility to perform in the future measurements of X rays (having such excellent X-ray detectors, as the CCDs and SDDs) generated as spontaneous radiation predicted by (some) collapse models. The collapse models deal with the "measurement problem" in quantum mechanics by introducing a new physical dynamics that naturally collapses the state vector. Collpase models make predictions which differ from those of standard quantum mechanics [18]. One of the most exciting task is to perform cutting-edge experiments, in order to asses whether quantum mechanics is exact, or an approximation of a deeper level theory.

In the nonrelativistic collapse model developed by Ghirardi, Rimini, Weber [19] and Pearle [20] (see also ref. [21] for a review), namely the continuous spontaneous localization (CSL) model, the state vector undergoes a nonunitary evolution in which particles interact with a fluctuating scalar field. This interaction has not only the effect of collapsing the state vector towards the particle number density eigenstates in position space, but it increases the expectation value of particle's energy as well. This means, for a free charged particle (as the electron) electromagnetic

radiation. This type of phenomenon is predicted by the CSL and is totally absent in the standard quantum mechanics.

In the paper [22] a pioneering work on this spontaneous emission of radiation was performed - the authors analysed X-ray data measured in an underground experiment and interpreted them as a limit for the combination of the CSL parameter λ/a^2. It was shown that the highest sensitivity is at few keV X-rays, exactly in the range where our detectors are ideal. We have done a similar analysis, with a very preliminary results [23]. We are presently performing a feasibility study to define a dedicated experiment to measure X rays coming from the spontaneous collapse models and improve by few orders of magnitude the actual limit.

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