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VIP-2 - Testing spin-statistics for electrons with high sensitivity

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Abstract. The VIP-2 (VIolation of the Pauli Exclusion Principle) experiment conducted at the Gran Sasso underground laboratory (LNGS) of INFN is searching for possible tiny violations of standard quantum mechanics in copper atoms with extremely high sensitivity. We investigate atomic transitions with precision X-ray spectroscopy in order to test the Pauli Exclusion Principle (PEP) and therefore the spin-statistics theorem. We present the experimental method for the search for "anomalous" (i.e. Pauli-forbidden) X-ray transitions in copper atoms, produced by "new" electrons, which could have a tiny probability to undergo a Pauli-forbidden transition to the 1s ground state already occupied by two electrons. We describe the VIP-2 experimental setup and its recent optimisations. Presently VIP-2 is taking data at LNGS. The goal of VIP-2 is to test PEP for electrons with unprecedented accuracy, down to a limit in the probability that PEP is violated at the level of 10^{-31} (and using a more elaborate analysis even 10^{-40}). We present current experimental results.



1. Introduction

The Pauli Exclusion Principle (PEP) is a consequence of spin-statistics. The consequences of PEP are extremely important and have many aspects, like stability of matter, existence of neutron stars, superconductivity etc. Wolfgang Pauli found the exclusion principle and got the nobel prize in 1925 [1] for PEP with electrons. Afterwards PEP was found to be valid for all fermions and fermionic systems. However it was figured out that an easy explanation for its existence is difficult to find. Pauli found a proof in his paper of 1940 [2]. Nature is consisting only of fermions with half-integer spin and bosons with integer spin. Fermions and bosons are obeying different statistics, i.e. the Fermi-Dirac and Bose-Einstein statistics respectively. Therefore, even a tiny violation would result in new physics with new effects showing up. Up to now no indications of PEP violation were experimentally found. Experiments were/are conducted for searching a PEP-violation with extremely high sensitivity. Our VIP and VIP-2 experiments in the underground laboratory LNGS of INFN belong to these experiments. Since any violation is expected to be tiny, it is mandatory to suppress background to the PEP violating signal (like cosmic radiation) as effectively as possible. VIP-2 is based on searches for Pauli-forbidden transitions in an open quantum system introducing "new" electrons (new to the system) via an electron current and looking via X-ray spectroscopy for PEP violating transitions. The VIP-2 experiment follows the method first used by Ramberg and Snow (RS) [3] nearly 30 years ago. The principle of VIP-2, which is an improved experiment following our VIP experiment is described below. In the literature one can find many different methods to test the Pauli Principle, described in ref. [4]. PEP violation is quantified by the quantity $\beta^2/2$ related to the theory of Ignatiev and Kuzmin [5]. People studied elementary as well as combined systems and dynamic as well as stable systems. Very strong limits were derived from stable system transitions [7, 8]. However, the Messiah-Greenberg super-selection rule [6] claims that Pauli-violating processes cannot be observed in stable systems with a given permutation symmetry. The VIP-2 experiment avoids the MG super-selection rule by the introducing "new" electrons into the system.

2. VIP-2 method for testing the PEP

In fig.1 the basic principle of the VIP-2 experiments is given. If a forbidden transition to the 1s state happens (the hyperfine structure cannot be resolved), it is shifted to lower energy by about 300 eV due to shielding. This energy shift can be resolved by precision X-ray spectroscopy. The test electrons are provided by a large current (i.e. large number of electrons) flowing in the copper foil of the experiment. The question "how new are these electrons?" was studied in ref. [9]. Recently another method was studied in the framework of VIP-2 based on the search for forbidden γ -ray transitions in Roman lead [10]. The description of the VIP-2 setup and its detection system is given in ref. [11].

After preliminary studies [12, 13, 14, 15] the VIP-2 experiment in its present form was installed in 2018 employing new silicon-drift detectors SDDs which provide large solid angle coverage, a new timing capability and excellent energy resolution in the region of interest around 8 keV. In the experiment we can use a current of up to 150A which yields a strongly improved $\beta^2/2$ value.

3. X-ray spectra of VIP-2

Fig.2 shows the X-ray spectra recorded with the SDDs. In the present analysis we used the analysis method of Ramberg-Snow, i.e. we subtracted from the data with current (data with possible violatig events) the data collected without current (data without PEP violating events). From this analysis [16] we get a preliminary value of

$$\beta^2/2 < 3.4 \cdot 10^{-29} \quad (1)$$

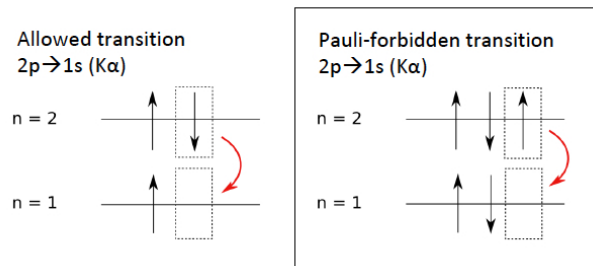


Figure 1. Allowed (left) and Pauli-forbidden (right) atomic transition to the filled 1s ground state in copper. The transition energy of the forbidden transition was calculated and found to be 300 eV lower. The hyperfine structure is neglected.

which is 3 orders of magnitude better than RS. By taking into account electron diffusion we get a limit of $\beta^2/2 < 2.6 \times 10^{-40}$ [9].

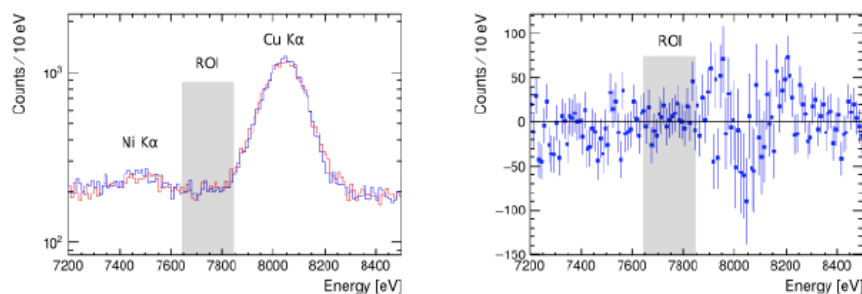


Figure 2. With SDDs measured X-ray spectra with and without current. The left figure shows the residual events after background subtraction in the region of interest.

4. Summary and Outlook

The experiments in the framework of VIP-2 steadily improve the upper limit on a possible PEP violation (see fig.3). Taking into account the diffusion of electrons in the copper bulk material we get an even stronger PEP violation limit. Due to the sensitivity of the PEP violation searches it was proposed to test different quantum gravity models with these experimental data [17] - thus testing the Planck energy regime which is not accessible by present particle accelerators. In summary the VIP-2 experiments and other experiments looking for PEP violation provide an instrument to search for new physics and to put stringent limitations on models in quantum gravity.

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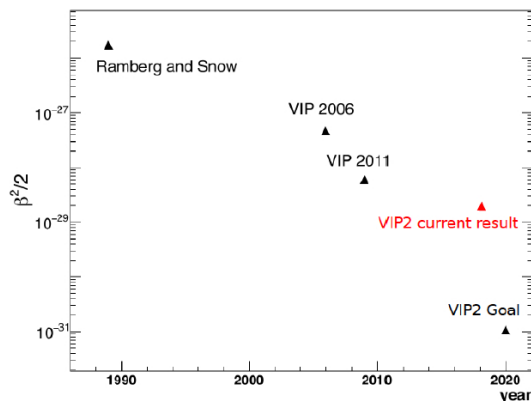


Figure 3. Upper limit for the PEP violation obtained in different experiments using the method and analysis of Ramberg-Snow. One assumes that electrons are on straight tracks which is certainly questionable. In the electron diffusion one deals with close encounters instead of straight tracks, and one gets several orders of magnitude lower limits.

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