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EXPERIMENTAL TESTS OF QUANTUM MECHANICS: PAULI EXCLUSION PRINCIPLE AND SPONTANEOUS COLLAPSE MODELS

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Abstract

The Pauli exclusion principle (PEP), as a consequence or the spin-statistics connection, is one of the basic principles of the modern physics. Being at the very basis of our understanding of matter, it spurs a lively debate on its possible limits, deeply rooted as it is in the very foundations of Quantum Field Theory. The VIP (VIolation of the Pauli exclusion principle) experiment is searching for a possible small violation of the PEP for electrons, using the method of searching for Pauli Exclusion Principle forbidden atomic transitions in copper. We describe the experimental method and the obtained results; we briefly present future plans to go beyond the actual limit by upgrading the experiment using vetoed new spectroscopic fast Silicon Drift Detectors. We also mention the possibility of using a similar experimental technique to search for possible X-rays generated in the spontaneous collapse models of quantum mechanics

1. Introduction

The Pauli Exclusion Principle (PEP), which plays a fundamental role in our understanding of many physical and chemical phenomena, is a consequence of the spin-statistics connection, (Pauli 1940), and, as such, it is intimately connected to the basic axioms of quantum field theory (Luders 1958). Although the principle has been spectacularly confirmed by the number and accuracy of its predictions, its foundation lies deep in the structure of quantum theory and has defied all attempts to produce a simple proof, as stressed for example by Feynman R.P. (Feynman 1963). Pauli himself in his Nobel lecture declared: ``...Already in my original paper I stressed the circumstance that I was unable to give a logical reason for the exclusion principle or to deduce it from more general assumptions.....The impression that the shadow of some incompleteness (falls) here on the bright light of success of the new quantum mechanics seems to me unavoidable".

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 (Bernabei 1997, Back 2005, Hilborn 1996, Nemo 2000, Nolte E. 1991 and Tsipenyuk 1998). Often, these experiments were born as by-products of experiments with a different objective (e.g., dark matter searches, proton decay, etc.), and most of the recent limits on the validity of PEP have been obtained for nuclei or nucleons.

In 1988 Ramberg E. and Snow G. (Ramberg 1990) performed a dedicated experiment, searching for anomalous X-ray transitions, that would point to a small violation of PEP in a copper conductor. The result of the experiment was a probability (Ignatiev 1997) $\beta^2/2 < 1.7 \times 10^{-26}$ that the PEP is violated by electrons.
The VIP Collaboration set up a much improved version of the Ramberg and Snow experiment, with a higher sensitivity apparatus, VIP Proposal (VIP Proposal 2004). Our final aim is to improve the PEP violation limit for electrons by 3-4 orders of magnitude, by using high resolution Charge-Coupled Devices (CCDs) as soft X-rays detectors (Culhane 1990), Egger 1993, Fiorucci 1990, Varidel 1990, Kraft 1995), and decreasing the effect of background by a careful choice of the materials and sheltering the apparatus in the LNGS underground laboratory of the Italian Institute for Nuclear Physics (INFN).
In the next sections we describe the experimental method and the experimental setup, the results of a first measurement performed in the Frascati National Laboratories (LNF) of INFN, along with results obtained by running VIP at the underground Gran Sasso National Laboratory (LNGS) of INFN.
We then briefly present future plans to go beyond the existing limit by using fast Silicon Drift Detectors (SDD) and a veto system.
We conclude the paper by presenting some ideas to use a similar experimental technique to perform measurements of X-rays predicted by spontaneous collapse models in quantum mechanics.

1. The VIP experiment

VIP is a dedicated experiment for the measurement of the probability of the Pauli Exclusion Principle violation for electrons. The experiment uses the same method of the Ramberg and Snow experiment, with a much better soft X-ray detector in a low-background experimental area - the INFN Gran Sasso underground laboratory. The detector is an array of Charge-Coupled Devices (CCDs), characterized by the excellent background rejection capability, based on pattern recognition, and good energy resolution (320 eV FWHM at 8 keV in the present measurement).

2.1 The Experimental Method

The experimental method consists in the introduction of ``fresh'' electrons into a copper strip, by circulating a current, and in the search for the X-rays resulting from the forbidden radiative transitions that occur if one of these electrons is captured by a copper atom and cascades to a 1S state which is already filled by two electrons. In particular we are looking for the 2P to 1S transition. The energy of this non-Paulian transition would differ from the normal transition energy by about 300 eV (7.729 keV instead of 8.040 keV), due to the additional screening effect given by the second electron on the 1S level, and was calculated using two different approaches (di Matteo 2006), providing an unambiguous signal of PEP violation. The new value is more precise than the rough estimate given in paper of Ramberg and Snow, where the shift, about 600 eV in that case, was approximated as the difference between the normal Copper transition from 2P to 1S level and the corresponding Nickel (Z-1 with respect to Copper) one, no real calculation of the PEP violating transition being done. 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, when we expect that the ``fresh'' electrons may undergo Pauli-forbidden transitions.

2.2 The VIP setup

The VIP setup consists of an empty copper cylinder, 45 mm radius, 50 μm thickness, and 88 mm height, surrounded by 16 equally spaced ``type 55'' CCDs made by EEV. The CCDs are at a distance of 23 mm from the copper cylinder, and paired one above the other. The setup is enclosed in a vacuum chamber, and the CCDs are cooled to about 168 K by a cryogenic system. The current flows in the thin cylinder made of ultrapure 99.995% copper foil from the bottom of the vacuum chamber. The CCDs surround the cylinder and are supported by cooling fingers which protrude from the cooling heads in the upper part of the chamber. The readout electronics is just behind the cooling fingers; the signals are sent to amplifiers on top of the chamber and the amplified signals are read out by ADC boards in the data acquisition computer.

More details on CCD-55 performance, as well on the analysis method used to reject background events, can be found in reference (Ishiwatari 2004, Ishiwatari 2006),
VIP improves very significantly on the Ramberg and Snow measurement, thanks to the following features:
- use of CCD detectors instead of gaseous detectors, having much better energy resolution (4-5 times better) and higher stability;
- experimental setup located in the clean, low-background, environment of the underground LNGS Laboratory;
- collection of much higher statistics (longer DAQ periods, thanks to the stability of CCDs).

2. The VIP experimental results

Before installation in the Gran Sasso laboratory, the VIP setup was prepared and tested at the LNF-INFN laboratory, where measurements were performed in the period 21 November - 13 December 2005. Two types of measurements were performed:
- 14510 minutes (about 10 days) of measurements with a 40 A current circulating in the copper target;
- 14510 minutes of measurements without current.

CCDs were read-out every 10 minutes. The resulting energy calibrated X-ray spectra are shown in figure 1.

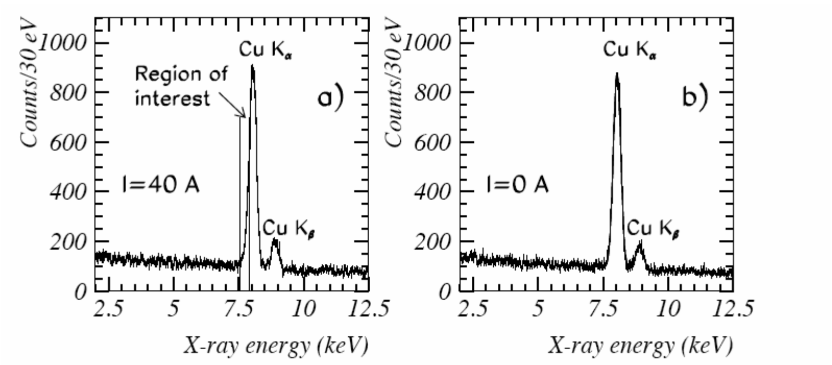

Fig. 1: Energy spectra with the VIP setup at LNF-INFN: a) with current (I=40 A); b) without current

These spectra include data from 14 CCD's out of 16, because of noise problems in the remaining 2.
Both spectra, apart from the continuous background component, display clear Cu lines due to X-ray fluorescence caused by the cosmic ray background and natural radioactivity. No other lines are present and this reflects the careful choice of the materials used in the setup. The subtracted spectrum is structureless. This not only yields an upper bound for a violation of the Pauli Exclusion Principle for electrons, but also confirms the correctness of the energy calibration procedure and points to the absence of systematic effects.
To extract the experimental limit on the probability that PEP is violated for electrons, $\beta^2/2$, from our data, we used the same arguments of Ramberg and Snow. See details in (Bartalucci 2006). The obtained value is:

$$\beta^2/2 < 4.5\times10^{-28} \qquad (1)$$

Thus with this first measurement in an unshielded environment, we have improved the limit obtained by Ramberg and Snow by a factor about 40.
The experiment was installed at LNGS-INFN in Spring 2006 , and was in data taking until Spring 2010, alternating period with current on (signal) to periods with current off (background).
We have established a preliminary new limit on PEP violation by electrons from data taken at LNGS:

$$\beta^2/2 < 4.7 \times 10^{-29} \qquad (2)$$

3. Future perspectives

The presented VIP setup uses CCD detectors, which are integrating detectors (no timing capability), for the measurement of the X-rays. In the future we plan to switch to a new type of detectors, namely the triggerable Silicon Drift Detectors (SSD), which have a fast readout time (1 μs), a large collection area (1 cm^2) and an energy resolution a factor about 2 better than the one of the used CCDs.

These detectors were successfully used in the SIDDHARTA experiment, (Bazzi 2009), for measurements of the kaonic atoms transitions at the DAFNE accelerator of LNF-INFN; using a proper trigger system a background rejection factor of the order of 10^{-4} was achieved in SIDDARTHA.

With these new detectors and with a more compact setup (higher acceptance) we expect a further reduction of the background produced by charged particles coming from the outside of the setup. It wasestimated that we can gain other 2-3 orders of magnitude in the $\beta^2/2$ factor.

Presently, the experimental setup is being under construction, with the aim to install it at LNGS in 2012.

Apart of the measurements of X rays related to the violation of PEP, we are presently considering the possibility to perform in the future measurements of X rays (exploiting these excellent X-ray detectors, 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. In the nonrelativistic collapse model developed by (Ghirardi 1986) and (Pearle 1989) (see also Bassi 2007 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 standard quantum mechanics.

In paper (Fu 1997) a pioneering work on this spontaneous emission of radiation was performed - the author analyzed X-ray data measured in an underground experiment and interpreted them as a limit for the CSL parameter(s). It was shown that the highest sensitivity is for few keV X-rays, exactly in the range where our detectors are ideal.

We plan to perform a feasibility study to define a dedicated experiment to measure X-rays coming from the spontaneous collapse models. In this way the same experimental technique would test different aspects of fundamental aspects of quantum theory.

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