Testing the Pauli Exclusion Principle for electrons

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Abstract.

The Pauli Principle represents one of the most important rules in physics and explains numerous phenomena as well as characteristic properties of matter, like its stability. Testing the validity of this principle at the highest possible sensitivity is a challenging experimental task - the VIP experiment at the Gran Sasso underground laboratory aims at a limit for the violation probability of the order of $10^{-29}$ to $10^{-30}$. The method is based on the search for Pauli-forbidden x-ray transitions in a pure copper conductor using silicon x-ray detectors with high resolution in energy. The experimental setup, results obtained so far and new ideas to further enhance the sensitivity will be presented.

1. Introduction

Wolfgang Pauli formulated a rule in 1925 which became the Pauli Exclusion Principle (PEP)[1]. PEP was remarkably successful and could easily explain the shell structure of the atoms. It was found that PEP is valid for all spin half particles, i.e. particles obeying the Fermi-Dirac statistics called fermions. In this way many features of nature, from stability of matter and neutron stars to the quark picture of hadrons found a clear explanation using PEP. On the other hand only with a complicated argumentation an explanation for PEP could be found by Pauli [2]. The Pauli principle has manifested its role as a pillar in quantum theory and should hold true to an extremely high level. The question about a tiny violation of PEP came up with the availability
Figure 1. VIP is searching for anomalous, Pauli-forbidden x-ray transitions in copper. The non-Paulian $K_\alpha$ transition energy would be shifted by about 300 eV from 8.040 to 7.729 keV.

of precision methods. In the last 20 years, several experiments have been performed to search for possible small PEP violations using different experimental approaches [3, 4, 5, 6, 7, 8].

For electrons Ramberg and Snow [9] performed a dedicated experiment at Fermilab, searching for PEP forbidden x-ray transitions giving a limit for the probability of PEP violation

$$\frac{\beta^2}{2} < 1.7 \times 10^{-26}. \quad (1)$$

The VIP (VIolation of the Pauli Exclusion Principle) Collaboration used a much improved version of the Ramberg and Snow experimental setup yielding a higher sensitivity [10]. The goal of VIP is an improvement of the PEP violation limit for electrons by several orders of magnitude. For the x-ray detectors an array of charged coupled devices (CCDs) [11, 12, 13, 14, 15] were used which provide excellent energy resolution and background reduction by selection of x-ray pixel hits. After first measurements at LNF-INFN the VIP apparatus was installed in the underground laboratory of LNGS (Laboratori Nazionali di Gran Sasso) of the Italian Institute for Nuclear Physics (INFN) which has the advantage of a highly suppressed background from cosmic rays.

2. Experimental Method

The VIP experiment is searching for Pauli-forbidden transitions in copper (see fig.1), i.e. the transition of an electron to the already fully occupied 1s state. The energy of the Pauli-forbidden $K_\alpha$ transition is shifted by about 300 eV, i.e. from 8.040 to 7.729 keV according to calculations [16]. The experiment uses the same experimental approach of the Ramberg-Snow experiment [9] in which the x-ray spectrum of a copper conductor with and without circulating current was compared.

2.1. Experimental setup

The VIP setup employs a thin cylinder of ultrapure (99.995%) copper (radius 45 mm, 88 mm height, thickness 50 µ) through which current is flowing (40 A). The circulating current of 40 A corresponds to $\sim 2.4 \times 10^{20}$/s test electrons probing the PEP validity. For the x-ray detection an array of 16 CCDs surround the copper target. These CCDs were successfully used for x-ray spectroscopy of kaonic atoms in the DEAR experiment [17]. The arrangement is installed in an insulation vacuum container in order to cool the CCD x-ray detectors to 170 K for obtaining the required high energy resolution. CCDs allow to single out x-ray events by analysis of the hit pattern thus suppressing background [18].
2.2. Results

Prior to the installation in the final destination in the Gran Sasso laboratory, the VIP apparatus was set up and tested at the LNF-INFN laboratory. First measurements were performed with current circulating in the copper target (about 10 days with 40A current) and a background measurement without current with the same measurement time. The obtained energy-calibrated x-ray spectra are shown in figure 2. The spectra show the copper x-ray lines sitting on the continuous background but no other x-ray lines proving the high purity of the structure materials used in the VIP setup.

From the x-ray spectrum with current the spectrum without current was subtracted and a value for the PEP violation factor $\beta^2/2$ was determined applying the Ramberg-Snow method [9]. Compared with the result of Ramberg-Snow the limit for PEP violation for electrons was improved by a factor of 40 [19].

$$\frac{\beta^2}{2} < 4.5 \times 10^{-28}$$

(2)

Vip was transferred to LNGS and continued the measurements with and without current. From the VIP data collected at LNGS a further improved limit (preliminary) for $\beta^2/2$ could be deduced:

$$\frac{\beta^2}{2} < 4.7 \times 10^{-29}$$

(3)
Figure 3. Progress in lowering the limit for PEP violation for electrons. The follow-up experiment VIP2 is aiming at a limit below $10^{-30}$.

3. Future Opportunities

The VIP setup uses CCD detectors which are excellent x-ray detectors in respect to energy resolution in the soft x-ray domain and background rejection based on pattern analysis. However, CCDs have no timing capability and therefore no active shielding of the apparatus against background is possible. To overcome this limitation new x-ray detectors, Silicon Drift Detectors (SSDs), are in consideration for the next VIP setup (VIP2). They provide excellent energy resolution comparable with CCDs, but have timing capability ($\Delta$FWHM $\approx 1\mu s$) and large detection area (100 mm$^2$) [21]. SDDs were successfully used in the SIDDHARTA experiment [22] for measurements of the x-ray spectra of kaonic hydrogen and kaonic helium isotopes at the DAΦNE accelerator of LNF-INFN. A compact design consisting of 6 SDDs looking at a cooled thin planar copper foil could be surrounded by anti-coincidence scintillation detectors. The setup will be additionally passively shielded by lead. With larger solid angle and possibly higher current - demanding high power cooling - a significantly higher sensitivity to non-Paulian transition in copper can be expected in the future.

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Figure 4. Design study of the inner part of a future setup employing 6 SDDs.

Figure 5. Schematic layout of the future apparatus. The inner part of the future setup will installed inside a lead housing thus active and passive shielding by lead is provided.

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