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The Pauli Exclusion Principle for electrons tested by VIP-2 at the LNGS laboratories

L. DE PAOLIS(1), S. BARTALUCCI(1), S. BERTOLUCCI(5), M. BAZZI(1),
M. BRAGADIREANU(1)(4), C. CAPOCCIA(1), M. CARGNELLI(3), A. CLOZZA(1),
R. DEL GRANDE(6)(1), C. FIORINI(7), C. GUARALDO(1), M. ILIESCU(1),
M. LAUBENSTEIN(8), J. MARTON(3), M. MILIUCCI(1), E. MILOTTI(9),
F. NAPOLITANO(1), A. PICHLER(3), K. PISCICCHIA(2), A. PORCELLI(3)(1),
A. SCORDO(1), H. SHI(3), D. L. SIRGHI(1)(4), F. SIRGHI(1)(4), F. SGARAMELLA(1),
J. ZMESKAL(3) and C. CURCEANU(1)(4)

(1) *INFN, Laboratori Nazionali di Frascati - Via E. Fermi 54, I-00044 Frascati(RM), Italy*
(2) *Centro Ricerche Enrico Fermi, Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi" - Via Panisperna 89a, I-00184 Roma, Italy*
(3) *Stefan Meyer Institute for Subatomic Physics - Kegelgasse 27, 1030 Wien, Austria*
(4) *Horia Hulubei National Institute of Physics and Nuclear Engineering Str. Atomistilor No. 407, P.O. Box MG-6 Bucharest-Magurele, Romania*
(5) *Dipartimento di Fisica e Astronomia, University of Bologna and INFN, Sezione di Bologna Via Irnerio 46, I-40126 Bologna, Italy*
(6) *Excellence Cluster Universe, Technische Universität München - Boltzmannstraße 2, 85748 Garching bei München, Germany*
(7) *Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria and INFN, Sezione di Milano - I-20133 Milano, Italy*
(8) *INFN, Laboratori Nazionali del Gran Sasso - Via G. Acitelli 22, I-67100 L'Aquila, Italy*
(9) *Dipartimento di Fisica, Università di Trieste and INFN, Sezione di Trieste - Via Valerio, 2, I-34127 Trieste, Italy*

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Summary. — The VIP-2 experiment tests the Pauli Exclusion Principle (PEP) in a copper target circulated by a Direct Current, hunting for atomic Kα transitions (2p $\rightarrow$ 1s) that violate the PEP. Silicon Drift Detectors (SDDs) are installed around the target to measure the atomic transitions with high-precision x-ray detectors. A PEP-violating Kα transition would occur if an electron arrived on the 1s orbital which is already occupied by two electrons. The energy of the Kα forbidden transition in copper is expected to be shifted down by about 300 eV with respect to the nominal energy of the Kα PEP-allowed transition ($\sim$8 keV). The SDD resolution is 190 eV (FWHM) at 8 keV and allows measuring and disentangling possible PEP-violating Kα transitions in copper. The VIP experiment sets an upper limit on the Pauli exclusion principle violation probability equal to $\beta^2/2 < 4.7 \times 10^{-29}$ for electrons in copper. The VIP-2 experiment, presently in data taken at the National Laboratories of Gran Sasso (LNGS) in Italy, aims at improving the VIP limit by two orders of magnitude. This paper will present a new preliminary upper limit obtained by analyzing two sets of data collected in a preliminary run with the VIP-2 apparatus.

1. – Introduction

The Pauli Exclusion Principle (PEP), deriving from the Spin Statistic Theorem (SST) [1], prevents two identical fermions from simultaneously occupying the same quantum state [2]. This principle represents a fundamental pillar of Quantum Mechanics. Its experimental investigation impacts in many fields of physics, and is relevant for the stability of matter [3] and neutron stars [4]. According to the SST, the total wave functions describing bosonic and fermionic states are, respectively, symmetrical and antisymmetrical with respect to the permutation of identical particles [5-7]. Moreover, the Messiah-Greenberg (MG) superselection rule [8] forbids transitions among different symmetry states in a given system of identical particles. A PEP violation would imply the existence of systems that follow new statistics, different from fermionic and bosonic ones. Because of the PEP, any atomic energy level cannot be occupied by more than two electrons with opposite spin quantum number. Therefore, atomic transitions to an energy level already occupied by two electrons violate the PEP.

The VIP-2 experiment investigates the PEP looking for PEP-violating Kα transition (2p $\rightarrow$ 1s) in copper. The energy of the Kα atomic transition in copper is $\sim$8.0 keV [9], whilst the estimated energy of the PEP-forbidden Kα transition is $\sim$7.7 keV. The downshift of 300 eV is due to the additional screening effect produced by the second electron occupying the 1s atomic level in case of PEP-violating transition. The VIP experiment sets an upper limit on the PEP violation probability for electrons in copper equal to $\beta^2/2 \leq 4.7 \times 10^{-29}$ [10]. In the formula, the term $\beta^2/2$ was introduced by Ignatiev and Kuzmin [11,12] and represents the probability of PEP violation. The VIP-2 experiment aims to improving the VIP upper limit by two orders of magnitude. In this work, the VIP-2 apparatus is presented, together with the preliminary result obtained by analyzing the first sets of data collected by the experiment.

2. – The VIP-2 experimental apparatus

The VIP-2 experimental apparatus [13-15] is presently taking data at National Laboratories of Gran Sasso (LNGS) in Italy. The LNGS are underground laboratories providing an extremely low cosmic background environment [16]. The VIP-2 target consists of 2 copper strips (20 mm in height, 71 mm in length, and 25 μm in thick each) circulated by 100 A Direct Current (DC). 32 Silicon Drift Detectors (SDDs) are installed in the apparatus, organized in 4 arrays (2×4 SDDs each), and placed two on each side of the copper target. Each SDD is 450 μm thick and has an active area of 0.64 cm^2. The SDDs are kept at a temperature of 150 K by a liquid argon cooling system. In this configuration, the SDDs provide an energy resolution of 190 eV FWHM at $\sim$8 keV [14]. A water cooling system maintains the copper strips temperature in the range of 20–25 °C in all operating conditions (with and without current), thus ensuring stable working conditions for the SDDs. The temperatures of the SDD arrays and the target are monitored with PT-100 sensors. A Fe-55 source installed below the target is used for energy calibration. The PEP violating Kα transition is expected at 7746.73 eV [15,17]. The SDDs, the target and the Fe-55 source are placed inside a vacuum chamber, which is kept at a pressure of 10^{-5} mbar. An external shielding consisting of an internal layer of copper bricks and an external layer of lead bricks is installed outside the apparatus to further reduce the background due to the underground natural radiations.

3. – VIP-2 preliminary result

In the VIP-2 experiment, data are collected in two different experimental modes: with 0 A circulating on target (*current mode off*) and with 100 A DC circulating on target (*current mode on*). Through the DC circulating current, newly-injected electrons are introduced into the target and can interact with copper atoms in an Open System, which fulfill the Messiah-Greenberg superselection rule [18]. Spectra with no current circulating in the target are collected as background reference.

In this paper, we present the analysis of two sets of data collected in preliminary runs of the VIP-2 apparatus. The first data set consists of 107 days of data (42 days collected in *current mode on* and 65 days in *current mode off*) collected before the external passive shielding installation. A second data set consists of 101 days of data (40 days collected in *current mode on* and 61 days in *current mode off*) collected with partial shielding (lateral walls). Spectra of this last period are shown in fig. 1. In April 2019, the shielding was completed by installing the top part. In this final configuration, the VIP-2 experiment is presently taking data.

We performed both Bayesian and Frequentist analyses based on a binned likelihood function, considering the two separate data sets, using RooFit and RooStat [19]. In the analyses, the counts were selected in the spectral range of interest (7647–7847 eV) for the possible observation of the copper PEP-violating Kα transition, and the background in the data collected in *current mode on* is constrained from the data collected in *current mode off* for each data set. A Frequentist analysis is performed using a one-sided test statistics [20, 21], and we used $CL_s = \frac{CL_{s+b}}{1-CL_b}$ at 90% confidence level. Using the same likelihood, a Bayesian analysis is performed providing a result obtained at 90% confidence using a flat prior for $\beta^2/2$. All the parameters are marginalized using the Monte Carlo Markov Chain numerical integration to obtain the one-dimensional posterior PDF of $\beta^2/2$. More details on the data analysis procedure are being published in a dedicated paper.

Both the data analyses provided a new upper limit on the probability of violation of PEP for electrons in copper:

$$\beta^2/2 \leq 4.3 \times 10^{-30} \tag{1}$$

at 90% confidence level, for both the Frequentist CLs and Bayesian methods.

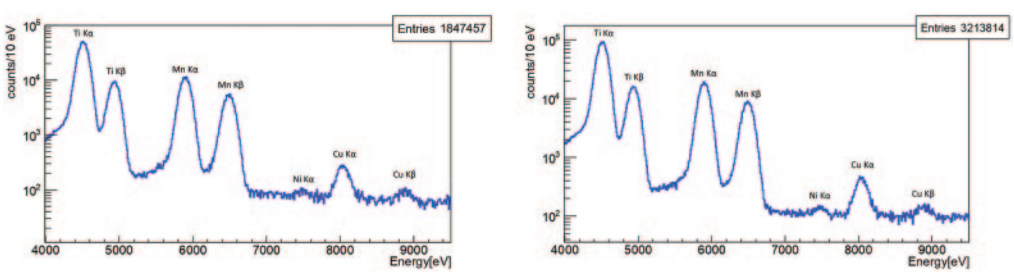

Fig. 1. – Spectra collected with the SDDs installed in the VIP-2 experiments, in partial shielding configuration (lateral walls). On the left, 40 days of data collected with 100 A DC circulating on target. On the right, 61 days of data collected with 0 A circulating on target. In the spectra, copper lines come from the target, whilst titanium and manganese lines come from the Fe-55 radioactive source, installed in the apparatus for detectors calibration. Moreover, the nickel line is coming from the detectors' ceramic support.

4. – Conclusions

Two sets of VIP-2 data of 107 and 101 days without and partial shielding, respectively, collected and analyzed by the VIP-2 collaboration, provide a new preliminary upper limit on the probability of violation of the Pauli Exclusion Principle for electrons in copper $\beta^2/2 < 4.3 \times 10^{-30}$ at 90% confidence level. The data were analyzed with both a Frequentist and a Bayesian analysis method. After these measurements, the shielding was completed in April 2019, and data taking resumed, with the goal of reaching an upper limit on $\beta^2/2$ one order of magnitude enhanced. For this objective, advanced analysis techniques, both from Frequentist and Bayesian inferences, will be used. Careful modeling of the background and signal, as well as statistical tests are in completion.

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