

# BEYOND QUANTUM MECHANICS? HUNTING THE ‘IMPOSSIBLE’ ATOMS — PAULI EXCLUSION PRINCIPLE VIOLATION AND SPONTANEOUS COLLAPSE OF THE WAVE FUNCTION AT TEST

K. PISCICCHIA<sup>a,b</sup>, C. CURCEANU<sup>a,b</sup>, S. BARTALUCCI<sup>a</sup>, A. BASSI<sup>c</sup>  
 S. BERTOLUCCI<sup>d</sup>, C. BERUCCI<sup>a,e</sup>, A.M. BRAGADIREANU<sup>a,f</sup>  
 M. CARGNELLI<sup>e</sup>, A. CLOZZA<sup>a</sup>, L. DE PAOLIS<sup>a</sup>, S. DI MATTEO<sup>g</sup>  
 S. DONADI<sup>c</sup>, A. D’UFFIZI<sup>a</sup>, J.-P. EGGER<sup>h</sup>, C. GUARALDO<sup>a</sup>  
 M. ILIESCU<sup>a</sup>, T. ISHIWATARI<sup>e</sup>, M. LAUBENSTEIN<sup>i</sup>, J. MARTON<sup>e</sup>  
 E. MILOTTI<sup>c</sup>, D. PIETREANU<sup>a,f</sup>, T. PONTA<sup>g</sup>, E. SBARDELLA<sup>a</sup>  
 A. SCORDO<sup>a</sup>, H. SHI<sup>a</sup>, D.L. SIRGHI<sup>a,f</sup>, F. SIRGHI<sup>a,f</sup>, L. SPERANDIO<sup>a</sup>  
 O. VAZQUEZ DOCE<sup>j</sup>, J. ZMESKAL<sup>e</sup>

<sup>a</sup>INFN Laboratori Nazionali di Frascati, Frascati (Roma), Italy

<sup>b</sup>Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi”, Roma, Italy

<sup>c</sup>Dipartimento di Fisica, Università di Trieste and INFN Sezione di Trieste  
 Trieste, Italy

<sup>d</sup>CERN, 1211, Geneva 23, Switzerland

<sup>e</sup>The Stefan Meyer Institute for Subatomic Physics, Vienna, Austria

<sup>f</sup>“Horia Hulubei” National Institute of Physics and Nuclear Engineering  
 Bucharest-Magurele, Romania

<sup>g</sup>Institut de Physique UMR CNRS-UR1 6251, Université de Rennes 1  
 Rennes, France

<sup>h</sup>Institut de Physique, Université de Neuchâtel, Neuchâtel, Switzerland

<sup>i</sup>INFN, Laboratori Nazionali del Gran Sasso, Assergi (AQ), Italy

<sup>j</sup>Excellence Cluster Universe, Technische Universität München  
 Garching, Germany

*(Received December 23, 2014)*

The development of mathematically complete and consistent models solving the so-called “measurement problem”, strongly renewed the interest of the scientific community for the foundations of quantum mechanics, among these the Dynamical Reduction Models possess the unique characteristic to be experimentally testable. In the first part of the paper, an upper limit on the reduction rate parameter of such models will be obtained, based on the analysis of the X-ray spectrum emitted by an isolated slab of germanium and measured by the IGEX experiment. The second part of the paper is devoted to present the results of the VIP (Violation of the Pauli exclusion principle) experiment and to describe its recent upgrade.

The VIP experiment established a limit on the probability that the Pauli Exclusion Principle (PEP) is violated by electrons, using the very clean method of searching for PEP forbidden atomic transitions in copper.

DOI:10.5506/APhysPolB.46.147

PACS numbers: 11.30.-j, 03.65.-w, 29.30.kv, 32.30.Rj

## 1. Upper limit on the wave function collapse mean rate parameter $\lambda$

The first consistent and satisfying Dynamical Reduction Model, known as Quantum Mechanics with Spontaneous Localization (QMSL) [1], considers particles undergoing spontaneous localizations around definite positions, following a Poisson distribution characterized by a mean frequency  $\lambda = 10^{-16} \text{ s}^{-1}$ . This brought to the development of the CSL theory [2] based on the introduction of new, non-linear and stochastic terms, in the Schrödinger equation besides to the standard Hamiltonian. Such terms induce, for the state vector, a diffusion process, which is responsible for the wave packet reduction. As demonstrated by Fu [3], the particle interaction with the stochastic field also causes an enhancement of the energy expectation value. This implies, for a charged particle, the emission of electromagnetic radiation (known as spontaneous radiation) not present in the standard quantum mechanics. The radiation spectrum spontaneously emitted by a free electron was calculated by Fu [3] in the framework of the non-relativistic CSL model, and it is given by:  $\frac{d\Gamma(E)}{dE} = \frac{e^2\lambda}{4\pi^2 a^2 m^2 E}$ , where  $m$  represents the electron mass,  $E$  is the energy of the emitted photon,  $\lambda$  and  $a$  are respectively the reduction rate parameter and the correlation length of the reduction model which is assumed to be  $a = 10^{-7} \text{ m}$ . If the stochastic field is assumed to be coupled to the particle mass density (mass proportional CSL model) (see, for example, [4]), then the previous expression for the emission rate is to be multiplied by the factor  $(m_e/m_N)^2$ , with  $m_N$  the nucleon mass. Using the measured radiation appearing in an isolated slab of germanium [5] corresponding to the energy of 11 KeV, Fu obtained the limit  $\lambda \leq 0.55 \times 10^{-16} \text{ s}^{-1}$ . In Ref. [6], the author argues that, in evaluating his numerical result, Fu uses for the electron charge the value  $e^2 = 17137.04$ , whereas the standard adopted Feynman rules require the identification  $e^2/(4\pi) = 17137.04$ . We took into account this correction when evaluating the new limit.

In order to reduce possible biases introduced on the  $\lambda$  value by the punctual evaluation of the rate at one single energy bin, the X-ray emission spectrum measured by the IGEX experiment [7, 8] was fitted in the range of  $\Delta E = 4.5 \div 48.5 \text{ KeV} \ll m$ , compatible with the non-relativistic assumption (for electrons) used in the calculation of the predicted rate. A Bayesian

model was adopted to calculate the  $\chi^2$  variable minimized to fit the X-ray spectrum, assuming the predicted energy dependence  $\frac{d\Gamma(E)}{dE} = \frac{\alpha(\lambda)}{E}$ . The result of the performed fit is shown in Fig. 1. The minimization gives for the free parameter of the fit the value  $\alpha(\lambda) = 110 \pm 7$ , corresponding to a reduced chi-square  $\chi^2/\text{n.d.f} = 1.1$ , from which the following upper limits can be set for the  $\lambda$  parameter:  $\lambda \leq 1.4 \times 10^{-17} \text{ s}^{-1}$  (non-proportional to mass) and  $\lambda \leq 4.7 \times 10^{-11} \text{ s}^{-1}$  (proportional to mass). The obtained limits improve the precedent Fu’s limit by a factor 4. Our results are to be compared with the values originally assumed in the models [1]:  $\lambda_{\text{QMSL}} = 10^{-16} \text{ s}^{-1}$ ,  $\lambda_{\text{CSL}} = 2.2 \times 10^{-17} \text{ s}^{-1}$  and with the values proposed, more recently, by Adler [6]. There is still plenty of space to investigate the collapse theory and its consequences.

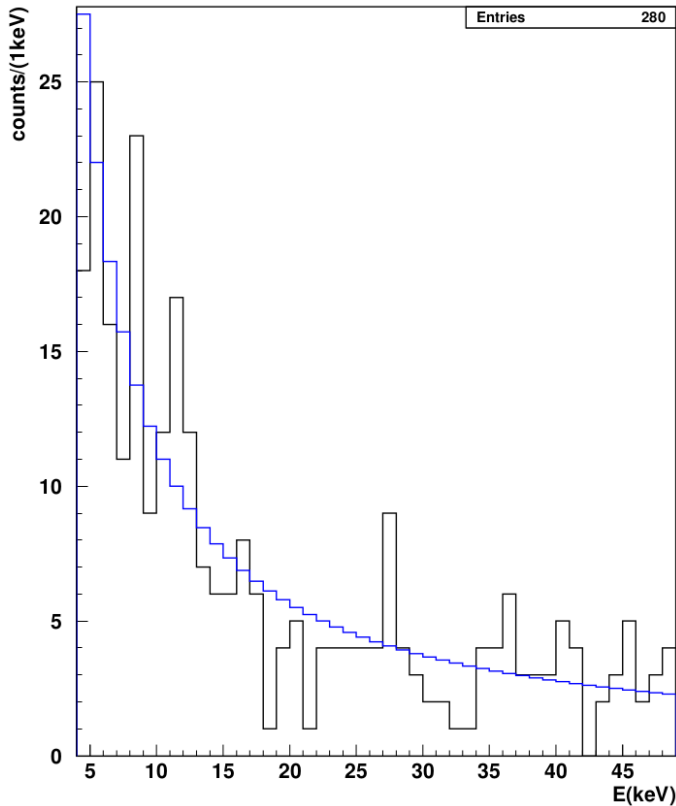


Fig. 1. Fit of the X-ray emission spectrum measured by the IGEX experiment [7, 8], performed assuming the predicted energy dependence  $\frac{d\Gamma(E)}{dE} = \frac{\alpha(\lambda)}{E}$ .

## 2. The VIP experiment and VIP upgrade

The PEP is a consequence of the spin-statistics connection [9], and, as such, it is intimately connected to the basic axioms of quantum field theory [10]. Given its basic standing in quantum theory, it is appropriate to carry out precise tests of the PEP validity and, indeed, mainly in the last 20 years, several experiments have been performed to search for possible small violations [11].

The VIP experiment is dedicated to the measurement of the PEP violation probability for electrons. VIP uses a method developed by Ramberg and Snow [12] (in agreement with the Messiah–Greenberg superselection rule [13]) consisting 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 PEP forbidden  $2P \rightarrow 1S$  ( $K_\alpha$ ) transitions that occur if one of these electrons is captured by a copper atom and cascades to a  $1S$  state already filled by two electrons. The energy of this non-Paulian transition would differ from the normal  $K_\alpha$  transition energy by about 300 eV (7.729 keV instead of 8.040 keV) [14]. The background is evaluated alternating periods without current in the copper strip.

The VIP Collaboration set up a much improved version of the Ramberg and Snow experiment, with a higher sensitivity apparatus [15]. The detector is an array of 16 Charge-Coupled Devices (CCDs) [16], characterized by excellent background rejection capability, based on pattern recognition and good energy resolution (320 eV FWHM at 8 keV in the present measurement). The background was reduced by a careful choice of the materials

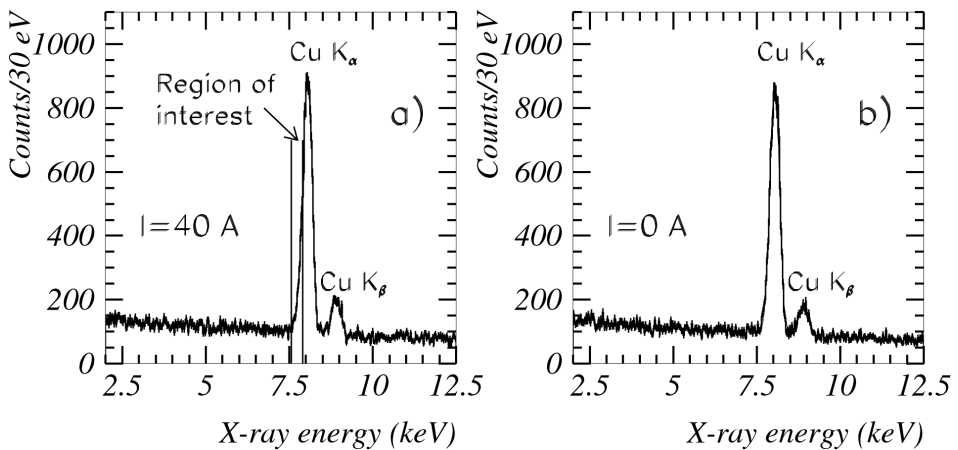


Fig. 2. Energy spectra with the VIP setup at LNF-INFN: (a) with current ( $I = 40$  A); (b) without current ( $I = 0$  A).

and sheltering the apparatus in the LNGS underground laboratory of the Italian Institute for Nuclear Physics (INFN). The VIP setup was taking data in a test period at LNF-INFN in 2005, and the resulting energy calibrated X-ray spectra, for the data taking with and without current, are shown in Fig. 2. These spectra include data from 14 CCDs out of 16, because of noise problems in the remaining 2. Both spectra, apart from the continuous background component, display clear Cu  $K_\alpha$  and  $K_\beta$  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, as for example the high purity copper and aluminium, the last one with  $K$ -complex transition energies below 2 keV. The setup was then installed in the Gran Sasso underground laboratory of INFN where it took data from 2006 until 2010.

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 references [12] and [17] for details of the analysis. The analysis of the LNGS data gives [18, 19]:  $\frac{\beta^2}{2} < 4.7 \times 10^{-29}$ , which represents an improvement with respect to the previous Ramberg and Snow limit ( $\frac{\beta^2}{2} < 1.7 \times 10^{-26}$ ) of a factor  $\sim 300$ .

An improved version of the VIP setup was already tested at the LNF and will be installed in the LNGS in next months. Thanks to the substitution of CCDs with the triggerable Silicon Drift Detectors (SSD), characterized by a fast readout time ( $\simeq 1 \mu\text{s}$ ) and large collection area ( $100 \text{ mm}^2$ ), a more compact system was realized, which is shown in Fig. 3. Moreover, to further reduce the background, an external veto-system, which would eliminate a

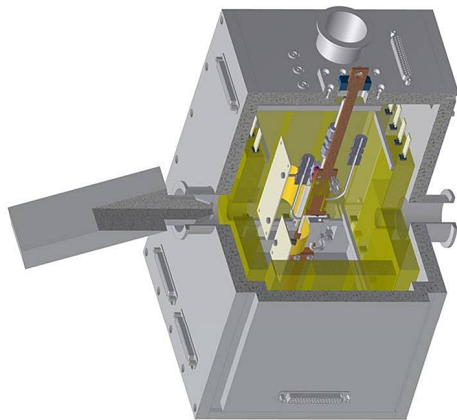


Fig. 3. The schematic implementation of the upgrade of the VIP experiment using SSD detectors and an external veto-system made of scintillators.

large part of the background produced by charged particles coming from the outside the setup, was employed. We expect to gain other 2 orders of magnitude in the limit on the probability of PEP violation, bringing it in the  $10^{-31}$  range.

## REFERENCES

- [1] G.C. Ghirardi, A. Rimini, T. Weber, *Phys. Rev.* **D34**, 470 (1986); **D36**, 3287 (1987); *Found. Phys.* **18**, 1 (1988).
- [2] P. Pearle, *Phys. Rev.* **A39**, 2277 (1989).
- [3] Q. Fu, *Phys. Rev.* **A56**, 1806 (1997).
- [4] A. Bassi, G.C. Ghirardi, *Phys. Rep.* **379**, 257 (2003).
- [5] H.S. Miley *et al.*, *Phys. Rev. Lett.* **65**, 3092 (1990).
- [6] S.L. Adler, *J. Phys. A* **40**, 2935 (2007).
- [7] C.E. Aalseth *et al.* [IGEX Collaboration], *Phys. Rev.* **C59**, 2108 (1999).
- [8] A. Morales *et al.* [IGEX Collaboration], *Phys. Lett.* **B532**, 8 (2002).
- [9] W. Pauli, *Phys. Rev.* **58**, 716 (1940).
- [10] G. Lüders, B. Zumino, *Phys. Rev.* **110**, 1450 (1958).
- [11] R. Arnold *et al.*, *Eur. Phys. J.* **A6**, 361 (1999); H.O. Back *et al.*, *Eur. Phys. J.* **C37**, 421 (2004); A. Barabash, *Found. Phys.* **40**, 703 (2010); A.S. Barabash *et al.*, *JETP Lett.* **68**, 112 (1998); P. Belli *et al.*, *Phys. Lett.* **B460**, 236 (1999); G. Bellini *et al.*, *Phys. Rev.* **C81**, 034 (2010); R. Bernabei *et al.*, *Phys. Lett.* **B408**, 439 (1997); R. Bernabei *et al.*, *Eur. Phys. J.* **C62**, 327 (2009); Y. Suzuki *et al.*, *Phys. Lett.* **B311**, 357 (1993).
- [12] E. Ramberg, G.A. Snow, *Phys. Lett.* **B238**, 438 (1990).
- [13] A.M.L. Messiah, O.W. Greenberg, *Phys. Rev.* **136**, B248 (1964).
- [14] S. Di Matteo, L. Sperandio, VIP Note, IR-04, April 26, 2006; The energy shift has been computed by P. Indelicato, private communication.
- [15] The VIP proposal, LNF-LNGS Proposal, September, 2004, <http://www.lnf.infn.it/esperimenti/vip>
- [16] J.L. Culhane, *Nucl. Instrum. Methods* **A310**, 1 (1990); J.-P. Egger, D. Chatellard, E. Jeannet, *Particle World* **3**, 139 (1993); G. Fiorucci *et al.*, *Nucl. Instrum. Methods* **A292**, 141 (1990); D. Varidel *et al.*, *Nucl. Instrum. Methods* **A292**, 147 (1990); R.P. Kraft *et al.*, *Nucl. Instrum. Methods* **A361**, 372 (1995).
- [17] S. Bartalucci *et al.* [VIP Collaboration], *Phys. Lett.* **B641**, 18 (2006).
- [18] L. Sperandio, Ph.D. Thesis, “New Experimental Limit on the Pauli Exclusion Principle Violation by Electrons from the VIP Experiment”, University “Tor Vergata”, Roma, March 5, 2008.
- [19] C. Curceanu *et al.*, *J. Phys. Conf. Ser.* **306**, 012036 (2011).