PROCEEDINGS OF SCIENCE

Underground Tests of Quantum Mechanics at Gran Sasso

Catalina Curceanu,[a,d,*] Fabrizio Napolitano,[a] Sergio Bartalucci,[a] Sergio Bertolucci,[b] Massimiliano Bazzi,[a] Mario Bragadireanu,[a,d] Cesidio Capoccia,[a] Michael Cargnelli,[e] Alberto Clozza,[a] Luca De Paolis,[a] Raffaele Del Grande,[a,g] Carlo Fiorini,[h] Carlo Guaraldo,[a] Mihail Iliescu,[a] Matthias Laubenstein,[i] Johann Marton,[e,a] Marco Miliucci,[a] Edoardo Milotti,[c] Kristian Piscicchia,[f,a] Alessio Porcelli,[e,a] Alessandro Scordo,[a] Francesco Sgaramella,[a] Hexi Shi,[e] Diana Laura Sirghi,[a,d] Florin Sirghi[a,d] and Johann Zmeskal[e]

[a] *INFN, Laboratori Nazionali di Frascati, Via E. Fermi 54, I-00044 Roma, Italy*
[b] *Dipartimento di Fisica e Astronomia, Università di Bologna, Via Irnerio 46, I-40126 Bologna, Italy*
[c] *Dipartimento di Fisica, Università di Trieste and INFN-Sezione di Trieste, Via Valerio 2, I-34127 Trieste, Italy*
[d] *IFIN-HH, Institutul National pentru Fizica si Inginerie Nucleara Horia Hulubei, Str. Atomistilor No. 407, P.O. Box MG-6 Buchares-Magurele, Romania*
[e] *Stefan-Meyer-Institute for Subatomic Physics, Austrian Academy of Science, Kegelgasse 27, 1030 Vienna, Austria*
[f] *Centro Ricerche Enrico Fermi–Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Via Panisperna 89a, I-00184 Roma, Italy*
[g] *Physik Department E62, Technische Universität München, James-Franck-Straße 1, 85748 Garching, Germany*
[h] *Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria and INFN Sezione di Milano, I-20133 Milano, Italy*
[i] *Laboratori Nazionali del Gran Sasso, INFN, Via G. Acitelli 22, I-67100 L'Aquila, Italy*

E-mail: Catalina.Curceanu@lnf.infn.it, napolitano.fabrizio@lnf.infn.it

Quantum mechanics is a cornerstone of modern physics and at the very basis of the Standard Model. However, decades-old open questions at its foundations, such as the "measurement problem" is still with us. Moreover, theories beyond the Standard Model often include extra-dimensions and violation of the Lorentz/Poincaré symmetries which could entail a departure from the predictions of the standard quantum mechanics. At the Gran Sasso underground laboratory in Italy, we search for small, beyond the quantum theory signals using radiation detectors. In particular, emission of spontaneous radiation is predicted by gravity-related and continuous spontaneous localization (CSL) collapse models. We have ruled out the natural parameter-free version of the Diósi-Penrose (DP) model, and put stringent limits on the CSL model. In addition, with the VIP-2 experiment we are searching for possible violations of the Pauli Exclusion Principle (PEP) in forbidden atomic transitions. The impact of this research on quantum gravity models, as well as its experimental upgrade VIP-3 is also discussed.

DISCRETE2021
29th November to 3rd December, 2021
Bergen, Norway

[*] Speaker

PoS(DISCRETE2020-2021)005

1. Introduction

The theory of quantum mechanics has demonstrated its validity in describing the microscopic world since the last century. It was therefore employed in its relativistic field formulation in the construction of the Standard Model (SM), which successfully describes the electroweak and strong interactions. While great scientific effort has been put in place to investigate its validity, there are few shortcomings both from the experimental and theoretical points of view. Dark Matter and Dark Energy, neutrino masses, matter-antimatter asymmetry are few important examples. The main theoretical challenge the SM faces is the role and the inclusion of gravity. Precision tests of quantum mechanics have a two-facets relevance to modern physics. The first one, which we may call *bottom-up*, starts from the main unanswered question at the basis of the quantum theory, which may hint the best direction to a better comprehension of the laws of nature. This is the case of the so-called measurement problem connected to the wave function collapse. The debate around the collapse was started by Schrödinger himself [1], in his cat paradox. Microscopic systems can be in superposition of states, and their evolution follows the linearity of the Schrödinger equation. To account for the quantum collapse, it was soon suggested that this evolution breaks downs after a certain scale, to explain the absence of superposition in macroscopic objects [2–7]. The wave function collapse, while accounting for the experimental evidence, still lacks a fundamental explanation.

One model has been proposed by R. Penrose and L. Diósi independently, where the gravitational self-potential of objects in superposition of states plays a major role [8–12]. The time of collapse can be expressed by:

$$\tau_{\mathrm{DP}} = \frac{\hbar}{\Delta E_{\mathrm{DP}}}. \tag{1}$$

The gravitational self interaction is measured by ΔE_{DP}. For macroscopic objects, this leads to instantaneous wave function collapse, i.e. no superposition is possible at all. The model predicts [13] the emission of spontaneous radiation with a rate $\mathrm{d}\Gamma_t/\mathrm{d}\omega_k$ per unit frequency ω_k, which happens as a result of the charged particles' random motion following the collapse. It can be written as:

$$\frac{\mathrm{d}\Gamma_t}{\mathrm{d}\omega_k} = \frac{2}{3}\frac{Ge^2N^2N_a}{\pi^{3/2}\epsilon_0 c^3 R_0^3\omega_k}. \tag{2}$$

Here G,e,ϵ_0 and c are the gravitational constant, the electron charge, the vacuum permittivity and the speed of light; N_a is the total number of atoms. The parameter R_0 was suggested by Penrose as the size of the nucleus wave function, but can be treated as a free parameter of the model, as we will see in Section 2.1.

Another important collapse model is the Continuous Spontaneous Localization (CSL) model [14–18], where the wave function collapse occurs as a consequence of the interaction with an external noise. In this case, the radiation emission rate is expressed as:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = A\frac{\hbar\lambda}{4\pi^2\epsilon_0 m_0^2 r_C^2 c^3 E} \tag{3}$$

where A in this case takes different forms if the emission is coherent or incoherent, E is the radiation energy, and the model parameters r_C and λ are the collapse spatial resolution and the strength of the noise, respectively. As shown in Section 2.1, we have strongly constrained the parameter space of the DP and CSL model by searching for the predicted radiation of both models.

PoS(DISCRETE2020-2021)005

The other research line, *top-down*, consists of looking for beyond the SM effects on quantum mechanics. This is the case of a class of quantum gravity theories which are referred to as Non-Commutative Quantum Gravity (NCQG). The idea of the non-commutativity of space-time was firstly introduced by W. Heisenberg [19–21], and was afterwards employed in the context of string theory [22] and loop quantum gravity [23]. The NCQG theories deform the Poincaré symmetry, κ-Poincaré and θ-Poincaré (e.g. [24, 25]). The deformation of fundamental symmetries in these scenarios, even if suppressed at low energies, could induce a violation of the Pauli Exclusion Principle (PEP), which directly related to the Spin Statistics theorem (SST) and Lorentz/Poincaré symmetry. PEP violation was parametrized by Ignatiev and Kuzmin [26] in terms of a three level Fermi oscillator. In their formalism, β is the amplitude parameter connecting the forbidden states to allowed states, and $\beta^2/2$ represents the violation probability. As shown in Section 2.2, precision measurements can place stringent limits on the $\beta^2/2$ parameter, and have the potential to constrain classes of NCQG theories.

2. Experimental Results at LNGS

We perform precision tests of quantum mechanics and beyond the SM theories in the low radiation environment of the INFN's national underground laboratories (LNGS), under the Gran Sasso mountain in central Italy. With an overburden of around 3500 meters of water equivalent shielding provided by the mountain rocks, the LNGS is an ideal laboratory for searches involving rare events. The cosmic radiation is reduced by six orders of magnitude, and the main background originates mostly from environmental radiation. Section 2.1 introduces the setup and the results of the study of the collapse models. Section 2.2 is focussed on experimental searches for the PEP violation.

2.1 Collapse Models

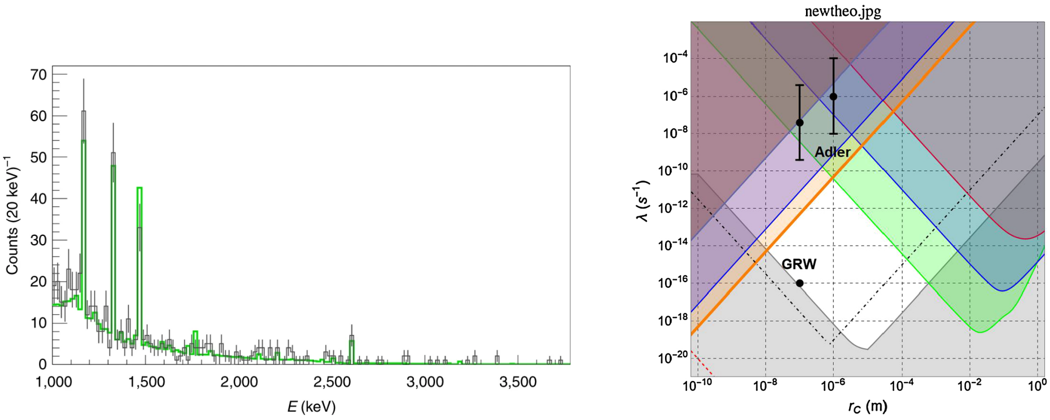
Since both the DP and CSL models predict the emission of faint, spontaneous radiation at the time of collapse, it is possible to investigate these models in the clean environment of LNGS. We use a coaxial p-type high-purity germanium detector, which is heavily shielded to further reduce contamination from environmental γ-radiation [13]. From the inside out, a germanium crystal is surrounded by an inactive layer of lithium-doped germanium. The total active volume is 375 cm^3. Electrolytic copper and lead are used for the inner and outer shielding.

A Monte Carlo simulation was performed to account for residual cosmic radiation and radionuclide contamination in the setup. The acquired spectrum is shown in Figure 1a, together with the simulation. A statistical analysis was performed, taking into account the signal shape and the detection efficiency. Since no significant amount of events was found above the expected ones, an upper limit on the R_0 parameter was placed [13]:

$$R_0 > 0.54 \times 10^{-10}\ \text{m}. \tag{4}$$

This result rules out the parameter-free version of the DP model, where the R_0 is fixed by the wave function size in the germanium crystal ($R_0 = 0.05 \times 10^{-10}$ m).

The same germanium detector, used for the study of the DP model, was also employed for the CSL collapse model. Since again, no significant amount of signal events are found above the expected



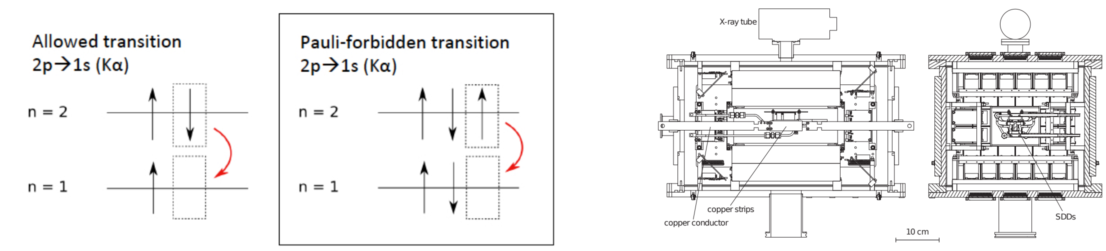
(a) Acquired spectrum. **(b)** The r_C vs λ CSL parameter space.

Figure 1: On the left, the spectrum acquired by the high purity germanium detector and its comparison with the Monte Carlo description between 1 and 3.8 MeV used to constrain the DP model [13]. On the right, the parameters space of the CSL model is shown. The constraints derived from the germanium detector are shown in orange [27].

ones, upper limits are placed [27]. In Figure 1b, the r_C-λ parameter space of the CSL model is shown. The black points correspond to proposed values by Adler [28, 29] and Ghirardi-Rimini-Weber (GRW) [5]. The gray band shows the exclusion from theoretical considerations. The green, blue and red bounds at higher r_C are obtained from gravitational wave detectors. The purple bound corresponds to the study of the emission of radiation; the orange bound comes from the germanium detector described in this section, and improve the previous results by a factor of 13.
Investigating wave function collapse models is a key milestone in precision tests on the foundations of quantum mechanics, since any possible deviations from the prediction of the standard quantum theory could hint a possible physics beyond the SM. By exploiting the low radiation of the Gran Sasso underground laboratories and state-of-the-art high purity germanium detectors, we have strongly constrained the parameter space still available, and ruled out parameter free models.

2.2 Pauli Exclusion Principle violations

Since Pauli's formulation in 1925 [30], the Exclusion Principle has been embedded in the development of quantum mechanics. Indeed, PEP lies in very few, general assumption as shown by Lüders and Zumino [31], such as CPT symmetry, Lorentz and Poincaré symmetries as well as unitarity, causality and locality. It is therefore natural to consider that any theories beyond the SM which entail a deformation, albeit small, of one of these principles, could have an effect on the PEP. In particular, quantum gravity models which assume a deformation of the commutativity of space-time as the NCQG models through alteration of the Poincaré symmetry, would have an effect even at lower energies [23–25].
The Messiah and Greenberg (MG) superselection rule [32] forbids transitions between states with different symmetries, i.e. it would not be possible to observe PEP violating processes without an interaction with an external, new fermion. Depending on how the new fermion is introduced, searches for PEP violations under the MG rule are can be performed in *open* systems, if the interaction is introduced from outside, and *closed* systems if not.



(a) **(b)**

Figure 2: On the left, the schematic representation of the PEP allowed $2p \rightarrow 1s$ transition, and the forbidden one which is under scrutiny in the VIP-2 experiment. On the right, later and transverse section of the VIP-2 setup.

Ignatiev and Kuzmin parametrized the violation in terms of a three level Fermi oscillator, with the violation probability historically expressed as $\beta^2/2$ [26], where β is the amplitude connecting the forbidden state to the allowed ones. At the LNGS, we are performing dedicated experiments looking for possible violation of the PEP in atomic transitions in open and closed systems [33].

2.3 VIP-2 Experiment

The VIP-2 open system experiment is targeting forbidden $2p \rightarrow 1s$ transitions in copper, as shown in Figure 2a, from the $2p$ state to the already-occupied $1s$ state, where the $2p$ electron is introduced via a strong direct current.

The increased shielding provided by the additional electron is responsible for an energy shift of the emitted X-ray, with respect to the energy of the standard Cu-K_α emission. This experimental method was first suggested by Greenberg and Mohapatra [34] and carried out by Ramberg and Snow [35].

In Figure 2b the experimental VIP-2 apparatus is shown in transverse section. The VIP-2 experiment is the successor of the VIP experiment, with the experimental goal of reaching $\beta^2/2 < 4 \times 10^{-31}$. To this end, it is equipped with state-of-the-art Silicon Drift Detectors (SDDs) with a resolution of 190 eV (FWHM) at 8 keV, developed in collaboration with the Stefan Meyer Institute, Politecnico di Milano and the Fondazione Bruno Kessler [36]. They guarantee a greater active area, thickness and quantum efficiency in the energy region considered, with respect to Charge Coupled Devices employed by the precedent VIP experiment.

The SDDs are operated at about -90 C° and placed in front of the copper target, comprised of two strips, each 71 mm long, 20 mm high and 25 µm thick, where a direct current of up to 180 A is circulated. A closed circuit chiller prevents the target from overheating. The target, SDDs and their front-end electronics are housed in a vacuum chamber, operated at 10^{-5} mbar. Additionally, a low activity Fe-55 radioactive source is present inside the setup in order to provide an in-situ calibration for the SDDs.

When the current is on, new electrons are injected inside the target. According to MG, they can test the PEP at each interaction with the copper atoms. If PEP is violated, the violating electrons would perform the forbidden $2p \rightarrow 1s$ transition, emitting a characteristic X-ray at a lower energy with respect to the standard electromagnetic K_α transition due to the shielding of the additional electron.

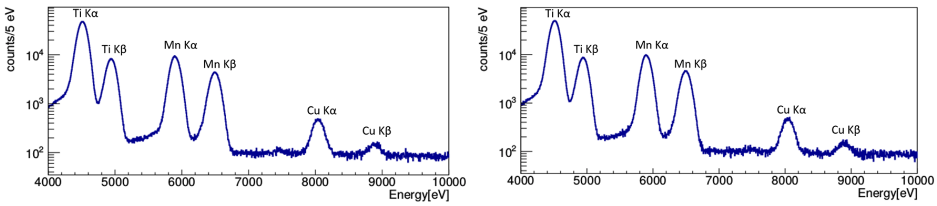


Figure 3: Energy calibrated spectra of 42 days collected by the VIP-2 in 2018 [37]. On the left (right), the spectrum acquired with current on (off) is presented. The titanium and manganese K_α and K_β lines are used for the in-situ calibration. The PEP violating signal in copper is expected at around 7.7 keV, below the copper K_α. The spectrum with current off is normalized to the data taking time with current on.

When the current is off, no signal is expected, and the data taken is used as control and reference for the data with current.

A preliminary result of the VIP-2 setup from [37] is shown in Figure 3, with the spectrum acquired in 2018 with current on (left) and off (right).

The upper limit on the signal yield was determined to be 178 events in the Region of Interest (ROI) 7647–7847 eV, which corresponds to a FWHM windows centered at the energy of the expected violating line. The limit was calculated at 90% confidence level with a Bayesian analysis with a flat prior for the signal. Taking into account the uncertainties, the 90% limit on the $\beta^2/2$ parameter becomes:

$$\frac{\beta^2}{2} < 1.2 \times 10^{-29}. \tag{5}$$

This limit is extracted the same way Ramberg and Snow did in their original experiment [35], i.e. considering the observed number of violating X-rays $N_X = \beta^2/2 \cdot N_{int} \cdot N_{new} \cdot 1/10 \cdot \epsilon$, where N_{int} is the number of scatterings of the electrons, N_{new} the number of new electrons introduced with the current, 1/10 is an estimate of the capture probability per scattering [35] and ϵ encodes the geometrical acceptance and the self-absorption of X-rays in the target material evaluated through a GEANT4 Monte Carlo simulation. However, a more complete picture of the interactions of the conduction electrons with the target material has been developed [38]. The electron scatterings is in fact caused by the interaction with phonons, defects and impurities, which rarely have to do with the electron capture process. Due to its Fermi velocity and material density, an electron will have a so-called "close encounter" with an atom in about $\tau = 3.5 \times 10^{-17}$ s. Consequently, the number of X-rays becomes $N_X = \beta^2/2 \cdot N_{int} \cdot N_{new} \cdot \epsilon$ where this time N_{int} becomes now T/τ, where $T = l/v_D$ is the time the electron takes to travel through l due to its drift velocity v_D. In this case, the exclusion limit on the PEP violation becomes [37]:

$$\frac{\beta^2}{2} < 5.4 \times 10^{-42}. \tag{6}$$

The VIP-2 experiment is presently taking data in its final configuration after the commissioning phase. It will provide an improvement of two orders of magnitude with respect to the previous VIP experiment. A data analysis of a partial statistics is in course of publication in peer-reviewed journals.

2.3.1 Towards VIP-3

As noted by L. B. Okun [39], the PEP enjoys a place so special in modern theoretical physics, that experimental tests investigating this fundamental principle should be carried out across the entire periodic table. The VIP collaboration is planning to perform dedicated searches for PEP violation with different target elements. To this purpose, a 1 mm thick SDD is being produced at Fondazione Bruno Kessler, in order to improve the quantum efficiency at higher X-ray energies. The additional thickness will provide a factor of two higher efficiency at 20 keV with respect to the 450 µm thick SDDs currently employed in the VIP-2 experiment. The new SDDs will guarantee to extend the experimental reach to silver, tin and palladium. A new apparatus is under finalization to house the new detector, presenting sensible improvements with respect to the present one. The new vacuum chamber for the VIP-3 experiment is optimized to arrange twice the number of the new SDDs and their front end electronics, with a total of 64 active channels. The new setup will allow to safely operate a direct current of up to 400A

3. Conclusions

Quantum Mechanics is being investigated on its foundations at the LNGS underground laboratory. The bottom-up approach starts from the measurement problem connected to the wave function collapse. Theories which modify the standard quantum dynamics have been put forward to explain the collapse, most notably the DP and CSL models. The spontaneous radiation emission they predict is testable, and detectable with high purity germanium detectors. We have put strong bounds on the CSL model [27] and ruled out the parameter-free version of the DP [13].
Theories beyond the Standard Model, such as quantum gravity, can assume a deformation of the commutativity of space-time as the NCQG. The deformation of the Poincaré symmetry at low energies is deeply linked to CPT, unitarity, causality and locality, and even a faint deformation would cause a violation of the Pauli Exclusion Principle. VIP-2 is a dedicated experiment, looking for PEP violation under the MG superselection rule. To this end, a strong direct current is circulated in a copper target, introducing new electrons which fulfil the superselection rule. The analysis of preliminary data shows the VIP collaboration is well on its way to the experimental target. In parallel, the VIP collaboration is finalizing the design of the successor upgraded VIP-3 experiment, which will be able to operate a greater number of detectors with a stronger current. The thickness of the SDD which are being produced will allow extending the reach of PEP violation searches to even higher energies.

Acknowledgments

This research was funded by the National Institute for Nuclear Physics (INFN, Italy) and by the Austrian Science Foundation (FWF), which supports the VIP2 project with the grants P25529-N20, project P 30635-N36 and W1252-N27 (doctoral college particles and interactions). This publication was made possible also through the support of Grant 62099 from the John Templeton Foundation. The opinions expressed in this publication are those of the authors and do not necessarily reflect the views of the John Templeton Foundation. We also thank the support of the H2020 FET project TEQ with grant 766900. We gratefully acknowledge support from Centro Ricerche Enrico Fermi

("Problemi aperti nella meccanica quantistica"project), and from Foundational Questions Institute (Grants No. FQXi-RFP-CPW-2008 and FQXi-MGB-2011). We thank H. Schneider, L. Stohwasser, and D. Stückler from Stefan-Meyer- Institut for their fundamental contribution in designing and building the VIP2 setup. We acknowledge the very important assistance of the INFN-LNGS laboratory staff during all phases of preparation, installation and data taking.

References

[1] Erwin Schrödinger. „die gegenwärtige sitation in der quantenphysik ii “. *Naturwissenschaften*, 23(49):823–828, 1935.

[2] Anthony J Leggett. Macroscopic quantum systems and the quantum theory of measurement. *Progress of Theoretical Physics Supplement*, 69:80–100, 1980.

[3] Steven Weinberg. Precision tests of quantum mechanics. In *THE OSKAR KLEIN MEMORIAL LECTURES 1988–1999*, pages 61–68. World Scientific, 2014.

[4] J. S. Bell and Alain Aspect. *Speakable and Unspeakable in Quantum Mechanics*. Cambridge University Press, June 2004.

[5] Gian Carlo Ghirardi, Alberto Rimini, and Tullio Weber. Unified dynamics for microscopic and macroscopic systems. *Physical review D*, 34(2):470, 1986.

[6] Stephen L. Adler. *Quantum Theory as an Emergent Phenomenon*. Cambridge University Press, August 2004.

[7] Steven Weinberg. Collapse of the state vector. *Physical Review A*, 85(6):062116, 2012.

[8] Roger Penrose. On gravity's role in quantum state reduction. *General relativity and gravitation*, 28(5):581–600, 1996.

[9] Roger Penrose. On the gravitization of quantum mechanics 1: Quantum state reduction. *Foundations of Physics*, 44(5):557–575, 2014.

[10] Richard Howl, Roger Penrose, and Ivette Fuentes. Exploring the unification of quantum theory and general relativity with a bose–einstein condensate. *New Journal of Physics*, 21(4):043047, 2019.

[11] Lajos Diosi. A universal master equation for the gravitational violation of quantum mechanics. *Physics letters A*, 120(8):377–381, 1987.

[12] Lajos Diósi. Models for universal reduction of macroscopic quantum fluctuations. *Physical Review A*, 40(3):1165, 1989.

[13] Sandro Donadi, Kristian Piscicchia, Catalina Curceanu, Lajos Diósi, Matthias Laubenstein, and Angelo Bassi. Underground test of gravity-related wave function collapse. *Nature Physics*, 17(1):74–78, September 2020.

[14] G. C. Ghirardi, A. Rimini, and T. Weber. Unified dynamics for microscopic and macroscopic systems. *Physical Review D*, 34(2):470–491, July 1986.

[15] Philip Pearle. Combining stochastic dynamical state-vector reduction with spontaneous localization. *Physical Review A*, 39(5):2277–2289, March 1989.

[16] Gian Carlo Ghirardi, Philip Pearle, and Alberto Rimini. Markov processes in hilbert space and continuous spontaneous localization of systems of identical particles. *Physical Review A*, 42(1):78–89, July 1990.

[17] Angelo Bassi and GianCarlo Ghirardi. Dynamical reduction models. *Physics Reports*, 379(5-6):257–426, 2003.

[18] Angelo Bassi, Kinjalk Lochan, Seema Satin, Tejinder P. Singh, and Hendrik Ulbricht. Models of wave-function collapse, underlying theories, and experimental tests. *Reviews of Modern Physics*, 85(2):471–527, April 2013.

[19] Letter of heisenberg to peierls (1930). *Wolfgang Pauli, Scientific Correspondence*, 2, 1985.

[20] Letter of pauli to oppenheimer (1946). *Wolfgang Pauli, Scientific Correspondence*, 3, 1993.

[21] R. Jackiw. Physical instances of noncommuting coordinates. *Nuclear Physics B - Proceedings Supplements*, 108:30–36, April 2002.

[22] Nathan Seiberg and Edward Witten. String theory and noncommutative geometry. *Journal of High Energy Physics*, 1999(09):032–032, September 1999.

[23] Suddhasattwa Brahma, Michele Ronco, Giovanni Amelino-Camelia, and Antonino Marcianò. Linking loop quantum gravity quantization ambiguities with phenomenology. *Physical Review D*, 95(4), February 2017.

[24] Michele Arzano and Jerzy Kowalski-Glikman. Deformed discrete symmetries. *Physics Letters B*, 760:69–73, September 2016.

[25] Andrea Addazi and Antonino Marcianò. A modern guide to θ-poincaré. *International Journal of Modern Physics A*, 35(32):2042003, November 2020.

[26] A Yu Ignatiev and V A Kuzmin. Search for slight violation of the pauli principle. *Pis'ma Zh. Eksp. Teor. Fiz.*, 77796:6–8. 5 p, Dec 1987.

[27] Sandro Donadi, Kristian Piscicchia, Raffaele Del Grande, Catalina Curceanu, Matthias Laubenstein, and Angelo Bassi. Novel CSL bounds from the noise-induced radiation emission from atoms. *The European Physical Journal C*, 81(8), August 2021.

[28] S.L. Adler. J. phys. a 40, 2935 (2007).

[29] S.L. Adler. J. phys. a 40, 13501 (2007).

[30] W. Pauli. Über den zusammenhang des abschlusses der elektronengruppen im atom mit der komplexstruktur der spektren. *Zeitschrift für Physik*, 31:765, February 1925.

[31] Gerhart Lüders and Bruno Zumino. Connection between spin and statistics. *Phys. Rev.*, 110:1450–1453, Jun 1958.

[32] A. M. L. Messiah and O. W. Greenberg. Symmetrization postulate and its experimental foundation. *Phys. Rev.*, 136:B248–B267, Oct 1964.

[33] Kristian Piscicchia, Edoardo Milotti, Aidin Amirkhani, Sergio Bartalucci, Sergio Bertolucci, Massimiliano Bazzi, Mario Bragadireanu, Michael Cargnelli, Alberto Clozza, Jean-Pierre Egger, et al. Search for a remnant violation of the pauli exclusion principle in a roman lead target. *The European Physical Journal. C, Particles and Fields.*, 80(6), 2020.

[34] O. W. Greenberg and R. N. Mohapatra. Local quantum field theory of possible violation of the pauli principle. *Phys. Rev. Lett.*, 59:2507–2510, Nov 1987.

[35] Erik Ramberg and George A. Snow. Experimental limit on a small violation of the pauli principle. *Physics Letters B*, 238(2):438–441, 1990.

[36] R. Quaglia, L. Bombelli, P. Busca, C. Fiorini, M. Occhipinti, G. Giacomini, F. Ficorella, A. Picciotto, and C. Piemonte. Silicon drift detectors and cube preamplifiers for high-resolution x-ray spectroscopy. *IEEE Transactions on Nuclear Science*, 62(1):221–227, 2015.

[37] Kristian Piscicchia, Johann Marton, Sergio Bartalucci, Massimiliano Bazzi, Sergio Bertolucci, Mario Bragadireanu, Michael Cargnelli, Alberto Clozza, Raffaele Del Grande, Luca De Paolis, Carlo Fiorini, Carlo Guaraldo, Mihail Iliescu, Matthias Laubenstein, Marco Miliucci, Edoardo Milotti, Fabrizio Napolitano, Andreas Pichler, Alessandro Scordo, Hexi Shi, Diana Laura Sirghi, Florin Sirghi, Laura Sperandio, Oton Vazquez Doce, Johann Zmeskal, and Catalina Curceanu. VIP-2 —high-sensitivity tests on the pauli exclusion principle for electrons. *Entropy*, 22(11):1195, October 2020.

[38] Edoardo Milotti, Sergio Bartalucci, Sergio Bertolucci, Massimiliano Bazzi, Mario Bragadireanu, Michael Cargnelli, Alberto Clozza, Catalina Curceanu, Luca De Paolis, Jean-Pierre Egger, Carlo Guaraldo, Mihail Iliescu, Matthias Laubenstein, Johann Marton, Marco Miliucci, Andreas Pichler, Dorel Pietreanu, Kristian Piscicchia, Alessandro Scordo, Hexi Shi, Diana Sirghi, Florin Sirghi, Laura Sperandio, Oton Vázquez Doce, Eberhard Widmann, and Johann Zmeskal. On the importance of electron diffusion in a bulk-matter test of the pauli exclusion principle. *Entropy*, 20(7):515, July 2018.

[39] L. B. Okun. On the Possibility of Pauli Principle Violation in Atoms. *JETP Lett.*, 46:529–532, 1987.