Quantum Mechanics studies in the Cosmic Silence

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On behalf of VIP Collaboration

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Content:

1) The VIP Scientific Case

2) Status of the VIP-2 experiment

3) VIP-2 preliminary results

4) Progress in the theoretical interpretation of the experimental results

5) VIP-lead preliminary limit on $\Theta$ - Poincarè

6) test of wave function collapse models
the VIP-2 scientific case
VIP-2 tests the Pauli Exclusion Principle (PEP) (spin-statistics) for electrons in a clean environment (LNGS) using a method which respects the Messiah-Greenberg superselection rule.
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Superpositions of states with different symmetry are not allowed → transition probability between two symmetry states is ZERO.

Closed system →

Open system →

VIP sets the best limit on PEP violation for an elementary particle respecting the M-G superselection rule.
Search for anomalous X-ray transitions performed by electrons introduced in a target through a DC current (open system)

\[ n=2 \quad \rightarrow \quad n=1 \quad \text{Normal } 2p \rightarrow 1s \text{ transition} \]

\[ n=2 \quad \rightarrow \quad n=1 \quad 2p \rightarrow 1s \text{ transition violating Pauli principle} \]

\[ \sim 8.05 \text{ keV in Cu} \quad \sim 7.7 \text{ keV in Cu} \]

Paul Indelicato (Ecole Normale Supérieure et Université Pierre et Marie Curie)

Multiconfiguration Dirac-Fock approach

Accounts for the shielding of the two inner electrons

The current-off spectrum provides the estimate of the background.
Search for anomalous electronic transitions in Cu induced by a circulating current ("new" external electrons, which interact with the valence electrons), namely transition from 2p to 1s already filled by 2 electrons, alternated to X-ray background measurements without current.
From VIP to VIP-2, the goal

a) copper ultrapure cylindrical foil
b) surrounded by 16 Charge Coupled Devices (CCD) res. at 8 keV 320 eV (FWHM)
c) inside a vacuum chamber: CCDs cooled to 168K by a cryogenic system
d) amplifiers + read out ADC boards.

\[ \beta^2/2 \leq 4.7 \times 10^{-29} \]

improved the limit obtained by Ramberg & Snow by a factor \( \sim 400 \)

(Foundation of Physics 41 (2011) 282+ other papers)

GOAL OF VIP-2 : improve the VIP result of 2 orders of magnitude
VIP-2 major upgrade

a) Silicon Drift Detectors (SDDs) → higher resolution (190 eV FWHM at 8.0 keV), faster (triggerable) detectors. 4 arrays of 2 x 4 SDDs 8mm x 8mm each, liquid argon closed circuit cooling - 170 °C

b) 2 strip shaped Cu targets (25 μm x 7 cm x 2 cm) more compact target → higher acceptance, thinner → higher efficiency
DC current supply to Cu bars

c) VETO system (32 plastic scintillators + SiPMs read out) → rejection of background (high energy charged particles) from outside the detector
VIP-2 preliminary results
May – June 2019
Bayesian data analysis procedure was implemented (inspired to A. Caldwell, K. Kröninger, Phys. Rev. D 74, 092003 (2006))

\[ p(S, B|\text{data}) = \frac{p(\text{data}|S, B) \cdot p_0(S) \cdot p_0(B)}{\int p(\text{data}|S, B) \cdot p_0(S) \cdot p_0(B) dS dB}. \]

Joint p.d.f. from the Bayes theorem. Number of events in each bin fluctuate around the mean according to a Pois. Dist.

Posterior p.d.f. (model needs in input the bkg. and sig. normalised shapes):

\[ P(S|\text{data}) = \int P(S, B|\text{data}) dB \]

Likelihood → \[ P(\text{data}|S, B) = \prod_{i=1}^{N} \frac{\lambda_i(S, B)^{n_i} \cdot e^{-\lambda_i(S, B)}}{n_i!} \]

Taking advantage of our last analysis the input normalised shape of the bkg spectrum is obtained from a symultaneous fit:


- PEP violation
- transition E
- SDD's resolution
- Normalised shape of the background
Bayesian data analysis procedure was implemented (inspired to A. Caldwell, K. Kröninger, Phys. Rev. D 74, 092003 (2006))

\[
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Posterior \textit{p.d.f.} (model needs in input the bkg. and sig. normalised shapes):

\[
P(S|\text{data}) = \int P(S, B|\text{data}) dB
\]

\[
\lambda_i = \lambda_i(S, B) = S \int_{\Delta E_i} f_S(E) dE + B \int_{\Delta E_i} f_B(E) dE.
\]

Taking advantage of our last analysis the input normalised shape of the bkg spectrum is obtained from a symultaneous fit:

\[
\text{Likelihood} \rightarrow P(\text{data}|S, B) = \prod_{i=1}^{N} \frac{\lambda_i(S, B)^{n_i} \cdot e^{-\lambda_i(S, B)}}{n_i!}.
\]
The prior probability for the number of expected signal events is assumed flat up to a maximum $S_{\text{max}}$ consistent with existing limits [Eur. Phys. J. C (2018) 78:319].

$$p_0(S) = \begin{cases} \frac{1}{S_{\text{max}}} & 0 \leq S \leq S_{\text{max}} \\ 0 & \text{otherwise} \end{cases}$$

The mean value for the expected number of bkg. Events $\mu_b$ mediated from the measured bkg. Spectrum. Prior is assumed Gaussian with a width $\sigma_b = \mu_b/2$.

The posterior is calculated by means of Markow chain Monte Carlo techniques

From which an upper limit on the PEP violation probability is obtained (90% Probability):

$$\beta^{2/2} < 2.6 \cdot 10^{-30}$$

$$\beta^{2/2} < 1.6 \cdot 10^{-41}$$
Progresses in the theoretical interpretation
Theories of Violation of Statistics


“Possible external motivations for violation of statistics include: (a) violation of CPT, (b) violation of locality, (c) violation of Lorentz invariance, (d) extra space dimensions, (e) discrete space and/or time and (f) noncommutative spacetime. Of these (a) seems unlikely because the quon theory which obeys CPT allows violations, (b) seems likely because if locality is satisfied we can prove the spin-statistics connection and there will be no violations, (c), (d), (e) and (f) seem possible…………..

Hopefully either violation will be found experimentally or our theoretical efforts will lead to understanding of why only bose and fermi statistics occur in Nature.”
Quantum gravity models can embed PEP violation transitions!

Prototype example is $\theta$-Poincarè non-commutative space-time.

$\theta$-Poincarè is explicitly unitary at tree level but $S$-matrix does not commute with CPT.

Moreover non-commutative space time implies non-locality and a-causality at the microscopic non-commutativity scale.

The spin statistics theorem was conceived assuming:

causality, locality, Lorentz invariance ..

$\theta$-Poincarè can elude the Pauli theorem
Differences of $\theta$-Poincarè w. r. to effective models:

- does not respect the M-G superselection rule (transition amplitude from a state of two different fermions to a state of two identical fermions is not zero) →

  can be tested with closed systems (ex. using Fermi see electrons in the conductor as test electrons, no current);

- the violation probability depends on the PEP violating process transition energy (suppressed with the non-commutativity energy scale) →

  it is important to test different atomic species → different $Z$ → different $\Delta E$ for the measured transition;

Preliminary test was already performed for $^{82}$Pb, we plan to repeat with other elements ($^{73}$Ta, $^{23}$V ...
High purity Ge detector measurement (Matthias Laubenstein):

- Ge detector surrounded by roman lead target + complex electrolytic Cu + Pb shielding

- 10B-polyethylene plates reduce the neutron flux towards the detector

- shield + cryostat enclosed in air tight steel housing flushed with nitrogen to avoid contact with external air (and thus radon).
Data analysis – normalised sig and bkg shapes

- Two data sets (total 71 days) August 2016-August 2017
- $f_B(E)$ flat in the range $\Delta E = (65 - 90)\text{keV}$ (standard transition lines do not emerge over flat bkg) mean bkg per bin: $b \sim 7$ counts/keV

Transitions in Pb
<table>
<thead>
<tr>
<th></th>
<th>forb.</th>
<th>allow.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1s - 2p$<em>{3/2}$ K$</em>{\alpha 1}$</td>
<td>73713</td>
<td>74961</td>
</tr>
<tr>
<td>1s - 2p$<em>{1/2}$ K$</em>{\alpha 2}$</td>
<td>71652</td>
<td>72798</td>
</tr>
</tbody>
</table>

\[ \lambda_i(S, B) = B \cdot \int_{\Delta E_i} f_B(E) \, dE + S \cdot \int_{\Delta E_i} f_S(E) \, dE \]

\[ f_B(B) = \frac{1}{\Delta E} \]

\[ f_S(E) = \frac{1}{\sqrt{2\pi \sigma^2}} \cdot \left[ p_1 \cdot e^{-\frac{(E-E_1)^2}{2\sigma^2}} + p_2 \cdot e^{-\frac{(E-E_2)^2}{2\sigma^2}} \right] \]

\[ p_1 = \frac{BR_{K_{\alpha 1}}}{BR_T}, \quad p_2 = \frac{BR_{K_{\alpha 2}}}{BR_T}, \]
**Data analysis – priors**

- PRIOR ON $B$ - a Poissonian distribution is assumed with expected value:
  \[ B_0 = b \cdot \Delta E \]

  (as a systematic effect a Gaussian prior was tried with no appreciable difference on the result)

- PRIOR ON $S$ - given the maximum expected number of signal events $S_{\text{max}}$ consistent with existing limits [Eur. Phys. J. C (2018) 78:319] we checked:
  - uniform prior \[ p_0(S) = \begin{cases} \frac{1}{S_{\text{max}}} & 0 \leq S \leq S_{\text{max}} \\ 0 & \text{otherwise} \end{cases} \]
  - exponential prior \[ p_0(S) = \frac{1}{S_{\text{max}}} \exp\left(-S/S_{\text{max}}\right) \]

  (no appreciable systematic effect from the prior choice on the result)
posterior is calculated by means of Markow chain Monte Carlo

Joint p.d.f.

Marginalised posterior

From which an upper limit on the PEP violation probability is obtained (90% Probability):

$$\frac{\beta^2}{2} = \frac{\bar{S}}{\epsilon_{tot} \cdot N_{Pb} \cdot \frac{\Delta t}{\tau_0}}$$

$$\beta^2/2 < 4.7 \cdot 10^{-46}$$

See also:
A. Addazi et al., Chinese Physics C 42(9), 2017
test of wave function collapse models
Measurement problem

The linear nature of QM allows superposition of macro-object states → Von Neumann measurement scheme (A. Bassi, G. C. Ghirardi Phys. Rep 379 257 (2003))

If we assume the theory is complete .. two possible ways out

• Two dynamical principles: a) evolution governed by Schrödinger equation (unitary, linear) b) measurement process governed by WPR (stochastic, nonlinear).

But .. where does quantum and classical behaviours split?

• Dynamical Reduction Models: non linear and stochastic modification of the Hamiltonian dynamics:


CSL - stochastic and nonlinear terms in the Schrödinger equation induce diffusion process for the state vector → reduction.

DIOSI – PENROSE - selfgravitating energy of the superposition gives the mean-life of the superposition - superposition of two space-times is suppressed proportionally to the mass characteristic parameter $R_0$ prediction ~ 1 fm
Test of the CSL and gravity-related collapse models

HPGe & LNGS 2014/2015 data campaigns
In coll. With A. Bassi & S. Donadi

According to collapse models, a collapsing white noise field induces spontaneous radiation emission.

The pdf of the models parameters is obtained within a Bayesian model:

$$\hat{p}(\Lambda_c | p(z_c | \Lambda_c)) = \frac{\Lambda_c^z e^{-\Lambda_c} \theta(\Lambda_c^{max} - \Lambda_c)}{\int_0^{\Lambda_c^{max}} \Lambda_c^z e^{-\Lambda_c} d\Lambda_c}$$

$$R_0 > 0.54 \times 10^{-10} \text{ m} \quad 95\% \text{ C. L.}$$

Diosi – Penrose ruled out in standard interpretation
Paper submitted to Science

Region Of Interest $\Delta E = (1000 - 3800) keV$
compatible with theoretical constrains

cosmic rays, bremsstrahlung
from $^{210}\text{Pb} & \text{daughters}$

counts / (1 keV)

K. Piscicchia et al.,
Entropy (2017) 19, 319

Best limit ever

$\lambda < 5.2 \cdot 10^{-13} \quad 95\% \text{ C. L.}$

three months data taking with 2kg Germanium active mass

Test of the CSL and gravity-related collapse models

Bounds on CSL parameters
Thank you :)
New veto system

Experimental setup and Monte Carlo model

Scheme of the setup with plastic scintillators as active shielding

New setup 2018
2 modules of 3.2 x 1.6 cm² (4x2 cells) SDDs on each side, each 500 μm thick
Cu: 2.0 x 9.0 cm² 25 μm thick
New refined data analysis (same data set) - simultaneous fit of the “sig + bkg” and bkg spectra, in order to use all the information available for the background shape from the data. The obtained fits:

Fig. 8 A global chi-square function was used to fit simultaneously the spectra with and without 100 A current applied to the copper conductor. The energy position for the expected PEP violating events is about 300 eV below the normal copper $K_{\alpha 1}$ transition. The Gaussian function and the tail part of the $K_{\alpha 1}$ components and the continuous background from the fit result are also plotted. (a): the fit to the wide energy range from 3.5 keV to 11 keV; (b): the fit and its residual for the 7 keV to 11 keV range where there is no background coming from the calibration source.
Improved limit on PEP violation probability:

$$\frac{\beta^2}{2} \leq \frac{3 \times 67}{6.0 \times 10^{30}} = 3.4 \times 10^{-29}$$

Https/doi.org/10.1140/epjc/s10052-018-5802-4
VIP-2 final setup gain factors

<table>
<thead>
<tr>
<th></th>
<th>VIP</th>
<th>VIP2</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>acceptance</td>
<td>1 %</td>
<td>7.7 %</td>
<td>~8</td>
</tr>
<tr>
<td>current</td>
<td>40 A</td>
<td>100 A</td>
<td>~2</td>
</tr>
<tr>
<td>X ray detection efficiency</td>
<td>0.4</td>
<td>0.99</td>
<td>~sqrt(2)</td>
</tr>
<tr>
<td>Energy resolution @ 8 keV</td>
<td>~350 eV</td>
<td>~190 eV</td>
<td>~sqrt(4)</td>
</tr>
<tr>
<td>Reduced active area</td>
<td>114 cm²</td>
<td>20 cm²</td>
<td>~sqrt(6)</td>
</tr>
<tr>
<td>Passive Shielding</td>
<td>Yes</td>
<td>No (Yet)</td>
<td>~sqrt(0.1)</td>
</tr>
</tbody>
</table>

+ MC simulations (preliminary) passive shielding contribution to the background reduction ~ sqrt(10)
**Transition energies of the anomalous X-rays in Copper**

**Paul Indelicato** (Ecole Normale Supérieure et Université Pierre et Marie Curie)

**Multiconfiguration Dirac-Fock approach**

**core:** \((1s)^2(2s)^2(3s)^2(2p^*)^2(3p^*)^2(2p)^4(3p)^4(3d^*)^4(3d)^2\)

<table>
<thead>
<tr>
<th>Transition</th>
<th>Initial en.</th>
<th>Final en.</th>
<th>Transition</th>
<th>Radiative transition energy</th>
<th>rate (s-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2p^{1/2} - 1s^{1/2})</td>
<td>-45799</td>
<td>-53528</td>
<td>7729</td>
<td></td>
<td>2.63E+14</td>
</tr>
<tr>
<td>(2p^{3/2} - 1s^{1/2})</td>
<td>-45780</td>
<td>-53528</td>
<td>7748</td>
<td></td>
<td>2.56E+14</td>
</tr>
<tr>
<td>(3p^{1/2} - 1s^{1/2})</td>
<td>-44998</td>
<td>-53528</td>
<td>8530</td>
<td></td>
<td>2.78E+13</td>
</tr>
<tr>
<td>(3p^{3/2} - 1s^{1/2})</td>
<td>-44996</td>
<td>-53528</td>
<td>8532</td>
<td></td>
<td>2.68E+13</td>
</tr>
</tbody>
</table>

**Normal copper:** \(~8050\) eV \((2p \rightarrow 1s)\)

**Note:** similar value obtained by S. Di Matteo e L. Sperandio in the “sudden approximation” - preprint LNF
this $\beta$ can be simply related to the $q$ parameter of the quon theory of Greenberg and Mohapatra

$$\frac{1}{2} \beta^2 = \frac{1 + q}{2}$$

quon algebra is a sort of weighted average between fermion and boson algebra:

$$\frac{1+q}{2} [a_k, a_l^+]_+ + \frac{1-q}{2} [a_k, a_l^+]_- = \delta_{kl}$$

or also

$$a_k a_l^+ - q a_l^+ a_k = \delta_{kl}$$
Pauli Exclusion Principle (PEP)

Several proofs exist in QFT which differ in clarity and quality of physical insight.

*Proof of spin-statistics theorem by Lüders and Zumino*

Postulates:

1. The theory is invariant with respect to the proper inhomogeneous Lorentz group (includes translations, does not include reflections)

2. Two operators of the same field at points separated by a spacelike interval either commute or anticommute (locality – microcausality)

3. The vacuum is the state of lowest energy

4. The metric of the Hilbert space is positive definite

5. The vacuum is not identically annihilated by a field

From these postulates it follows that (pseudo)scalar fields commute and spinor fields anticommute.

(G. Lüders and B. Zumino, Phys. Rev. 110 (1958) 1450)
Effective field theories of PEP violation

Ignatiev & Kuzmin model: Fermi oscillator with a third state

\[ a^+ |0\rangle |1\rangle \quad a |0\rangle 0 \quad a |1\rangle \]
\[ a^+ |1\rangle = \beta |2\rangle a^+ |2\rangle = 0 \quad |0\rangle a |2\rangle = \beta |1\rangle \]

\[ \beta \text{ quantifies the degree of violation in the transition } |1\rangle \rightarrow |2\rangle \]

Greenberg, O.W.; Mohapatra, R.N.
Local Quantum Field Theory, \( q \) parameter deforms anticommutators, quon theory

G. Gentile, NuovoCimento 17, 493(1940)
H. S. Green, Phys. Rev. 90 (1953) 270.
Measurement problem

The linear nature of QM allows superposition of macro-object states → Von Neumann measurement scheme (A. Bassi, G. C. Ghirardi Phys. Rep 379 257 (2003))

If we assume the theory is complete .. two possible ways out

- **Two dynamical principles:** a) evolution governed by Schrödinger equation (unitary, linear) b) measurement process governed by WPR (stochastic, nonlinear).
  But .. where does quantum and classical behaviours split?

- **Dynamical Reduction Models:** non linear and stochastic modification of the Hamiltonian dynamics:

QMSL - particles experience spontaneous localizations around appropriate positions, at random times according to a Poisson distribution with $\lambda = 10^{-16}$ s$^{-1}$.

CSL - stochastic and nonlinear terms in the Schrödinger equation induce diffusion process for the state vector → reduction.