A Letter by the Editor-in-Chief:

Twenty-Year Anniversary of the Orthopositronium Lifetime Anomalies: The Puzzle Remains Unresolved

This letter gives a history of two observed anomalies of orthopositronium annihilation, of which the 20th anniversary occurs this year. The anomalies, breaking the basics of Quantum Electrodynamics, require more experimental study, in view of the recent claim of the Michigan group of experimentalists, which alleges resolution of one of the anomalies.

It is now the 20th anniversary of the observation of anomalies of orthopositronium annihilation (both discovered in 1987) in experiments conducted by two groups of researchers: one group in the USA, headed by the late Prof. Arthur Rich in the University of Michigan at Ann Arbor, and the other group in Russia, headed by Dr. Boris Levin of the Institute of Chemical Physics in Moscow, but then at the Gatchina Nuclear Centre in St. Petersburg.

The anomalies dramatically break the basics of Quantum Electrodynamics.

Recently my long-time colleague, Boris Levin, one of the discoverers of the anomalies, suggested that the last experiment of the Michigan group, by which it has claimed resolution of one of the anomalies [1], was set up so that an electric field introduced into the experiment (it accelerates the particle beam before the target) mere suppressed the anomaly despite the electric field helps to reach complete thermalization of orthopositronium in the measurement cell. As a dry rest the anomaly, remaining represented but suppressed by the field, became mere invisible in the given experiment.

Now Levin proposes a modification of the last Michigan experiment in order to demonstrate the fact that the anomaly remains. He describes his proposed experiment in his brief paper appearing in this issue of Progress in Physics.

I would give herein a brief introduction to the anomalies (otherwise dispersed throughout many particular papers in science journals).

Positronium is an atom-like orbital system that contains an electron and its anti-particle, the positron, coupled by electrostatic forces. There are two kinds of positronium: parapositronium p-Ps, in which the spins of the electron and the positron are oppositely directed so that the total spin is zero, and orthopositronium o-Ps, in which the spins are co-directed so that the total spin is one. Because a particle-anti-particle system is unstable, life span of positronium is rather small. In vacuum parapositronium decays in $\sim 1.25 \times 10^{-10}$ s, while orthopositronium in $\sim 1.4 \times 10^{-7}$ s. In a medium the life span is even shorter because positronium tends to annihilate with electrons of the medium. Due to the law of conservation of charge parity, parapositronium decays into an even number of γ-quanta $(2, 4, 6, \dots)$ while orthopositronium annihilates into an odd number of γ-quanta $(3, 5, 7, \dots)$. The older modes of annihilation are less probable and their contribu-

tions are very small. For instance, the rate of five-photon annihilation of o-Ps compared to that of three-photon annihilation is as small as $\lambda_5 \approx 10^{-6} \lambda_3$. Hence parapositronium actually decays into two γ-quanta p-Ps $\to 2\gamma$, while orthopositronium decays into three γ-quanta o-Ps $\to 3\gamma$.

In the laboratory environment positronium can be obtained by placing a source of free positrons into matter, a monatomic gas for instance. The source of positrons is β^+-decay, self-triggered decays of protons in neutron-deficient atoms $p \to n + e^+ + \nu_e$. It is also known as positron β-decay.

Some of free positrons released into a gas from a β^+-decay source quite soon annihilate with free electrons and electrons in the container's walls. Other positrons capture electrons from gas atoms thus producing orthopositronium and parapositronium (in ratio 3:1).

The time spectrum of positron annihilations (number of events vs. life span) is the basic characteristic of their annihilation in matter. In particular, in such spectra one can see parts corresponding to annihilation with free electrons and annihilation of p-Ps and o-Ps.

In inert gases the time spectrum of annihilation of quasi-free positrons generally forms an exponential curve with a plateau in its central part, known as a "shoulder" [2, 3].

In 1965 P. E. Osmon published [2] pictures of observed time spectra of annihilation of positrons in inert gases (He, Ne, Ar, Kr, Xe). In his experiments he used ^{22}NaCl as a source of β^+-decay positrons. Analyzing the results of the experiments, Levin noted that the spectrum in neon was peculiar compared to those in other monatomic gases: in neon, points in the curve were so widely scattered that the presence of a "shoulder" was uncertain. Repeated measurements of time spectra of annihilation of positrons in He, Ne, and Ar, later accomplished by Levin [4, 5], have proven the existence of anomaly in neon. A specific feature of the experiments conducted by Osmon, Levin and some other researchers is that the source of positrons was ^{22}Na, while the moment of appearance of the positron was registered according to the γ_n-quantum of decay of excited ^{22*}Ne, ^{22*}Ne $\to ^{22}$Ne $+ \gamma_n$, from one of the products of β^+-decay of ^{22}Na. This method is quite justified and is commonly used, because the life span of excited ^{22*}Ne is as small as $\tau \simeq 4 \times 10^{-12}$ s, which is a few orders of magnitude less than those of the positron and parapositronium.

In his further experiments [6, 7] Levin discovered that the peculiarity of the annihilation spectrum in neon (abnormally widely scattered points) is linked to the presence in natural neon of a substantial quantity of its isotope ^{22}Ne (around 9%). Levin called this effect the *isotope anomaly*. Time spectra were measured in neon environments of two isotopic compositions: (1) natural neon (90.88% of ^{20}Ne, 0.26% of ^{21}Ne, and 8.86% of ^{22}Ne); (2) neon with reduced content of ^{22}Ne (94.83% of ^{20}Ne, 0.26% of ^{21}Ne, and 4.91% of ^{22}Ne). Comparison of the time spectra of positron decay revealed that in natural neon (composition 1) the shoulder is fuzzy, while in neon poor in ^{22}Ne (composition 2) the shoulder is always pronounced. In the part of the spectrum to which o-Ps decay mostly contributes, the ratio between intensity of decay in ^{22}Ne-poor neon and that in natural neon (with more ^{22}Ne) is 1.85 ± 0.1 [7].

The relationship between the anomaly of positron annihilation in neon and the presence of ^{22}Ne admixture, as shown in [6, 7], hints at the existence in gaseous neon of *collective nuclear excitation* of ^{22}Ne isotopes. In the terminal stage of β^+-decay nuclear excitation of ^{22*}Ne (life time $\sim 4\times10^{-12}$ s) is somehow passed to a set of ^{22}Ne nuclei around the source of positrons and is carried away by a nuclear γ_n-quantum after a long delay in the moment of self-annihilation of orthopositronium (free positrons and parapositronium live much shorter). Hence collective excitation of ^{22}Ne atoms seems to be the reason for the isotope anomaly. On the other hand, the nature of the material carrier that passes excitation of nuclear ^{22*}Ne to the surrounding ^{22}Ne atoms is still unclear, as is the means by which orthopositronium is linked to collective excitation − collective nuclear excitation is only known in crystals (Mössbauer effect, 1958).

In 1990 Levin [8] suggested, as a result of a relationship between orthopositronium and collective nuclear excitation, that a 1-photon mode of its annihilation should be observed. But decay of o-Ps into one γ-quantum would break the laws of conservation of Quantum Electrodynamics. To justify this phenomenological conclusion without breaking QED laws, Levin, in his generalised study [9], suggested that in the specific experimental environment, annihilation of some orthopositronium atoms releases one γ-quantum into our world and two γ-quanta into a mirror Universe, placing them beyond observation. But before any experiments are designed to prove or disprove the existence of such a "1-photon" mode, or any theory is developed to explain the observed effect, the problem still requires discussion.

Another anomaly is the substantially higher measured rate of annihilation of orthopositronium (the reciprocal to its life span) compared to that predicted by QED.

Measurement of the orthopositronium annihilation rate is among the main tests aimed at experimental verification of QED. Before the mid 1980's no difference between theory and experiment was observed, as measurement precision remained at the same low level.

In 1987, thanks to new precision technology, a group of researchers based at the University of Michigan (Ann Arbor) made a breakthrough in this area. The experimental results showed a substantial gap between experiment and theory. The anomaly that the Michigan group revealed was that measured rates of annihilation at $\lambda_{T(exp)} = 7.0514\pm0.0014\,\mu s^{-1}$ and $\lambda_{T(exp)} = 7.0482\pm0.0016\,\mu s^{-1}$ (to a precision of 0.02% and 0.023% using gas and vacuum methods [10–13] were much higher compared to $\lambda_{T(theor)} = 7.00383\pm0.00005\,\mu s^{-1}$ as predicted by QED [14–17]. The 0.2% effect was ten times greater than the measurement precision, and was later called the λ_T-anomaly [9].

In 1986 Robert Holdom [18] suggested that "mixed type" particles may exist, which, being in a state of oscillation, stay for some time in our world and for some time in a mirror Universe. In the same year S. Glashow [18] gave further development to the idea and showed that in the case of 3-photon annihilation o-Ps will "mix up" with its mirror twin, thus producing two effects: (1) a higher annihilation rate due to an additional mode of decay, o-Ps→nothing, because products of decay passed into the mirror Universe cannot be detected; (2) the ratio between orthopositronium and parapositronium numbers will decrease from o-Ps:p-Ps = 3:1 to 1.5:1. But because at that time (1986) no such effects were reported, Glashow concluded that no oscillation is possible between our-world and mirror-world orthopositronium.

On the other hand, by the early 1990's these theoretical studies motivated many researchers worldwide to an experimental search for various "exotic" (unexplained by QED) modes of o-Ps decay, which could shed some light on the abnormally high rate of decay. These were, to name just a few, search for o-Ps→nothing mode [20], check of possible contribution from 2-photon mode [21–23] or from other exotic modes [24–26]. As a result it has been shown that no exotic modes can contribute to the anomaly, while contribution of the o-Ps→nothing mode is limited to $< 5.8\times10^{-4}$ of o-Ps→3γ.

In a generalised study in 1995 [9] it was pointed out that the programme of critical experiments was limited to a search for the 1-photon mode o-Ps→$\gamma\backslash2\gamma'$ involving the mirror Universe and to a search for the mode o-Ps→nothing. The situation has not changed significantly over the past five years. The most recent publication on this subject, in May 2000 [27], still focused on the Holdom-Glashow suggestion of a possible explanation of the λ_T-anomaly by interaction of orthopositronium with its mirror-world twin, and on a search for the o-Ps→nothing mode. But no theory has yet been proposed to account for the possibility of such an interaction and to describe its mechanism.

The absence of a clear explanation of the λ_T-anomaly encouraged G. S. Adkins *et al.* [28] to suggest the experiments made in Japan [29] in 1995 as an alternative to the basic Michigan experiments. No doubt, the high statistical accuracy of the Japanese measurements [29] puts them on the same

level as the basic experiments [10–13]. But all the Michigan measurements possessed the property of a "full experiment", which in this particular case means no external influence could affect the wave function of positronium. Such an influence is inevitable due to the electrodynamic nature of positronium, and can be avoided only using special techniques. As was shown later, by Levin [31], this factor was not taken into account in Japanese measurements [29] and thus they do not possess property of a "full experiment".

As early as 1993 S. G. Karshenboim, one of the leaders in the theory, showed that QED had actually exhausted its theoretical capabilities to explain the orthopositronium anomalies [30]. The puzzle remains unresolved.

January 30, 2007   Dmitri Rabounski
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References

1. Vallery R. S., Zitzewitz P. W. and Gidley D. W. Resolution of the orthopositronium-lifetime puzzle. *Phys. Rev. Lett.*, 2003, v. 90, 203402 (1–4).

2. Osmon P. E. Positron lifetime spectra in noble gases. *Phys. Rev. B*, 1965, v. 138, 216.

3. Tao S. J., Bell J. and Green J. H. Fine structure in delayed coincidence lifetime curves for positron in argon. *Proc. Phys. Soc.*, 1964, v. 83, 453.

4. Levin B. M. and Shantarovich V. P. Annihilation of positrons in gaseous neon. *High Energy Chem.*, 1977, v. 11(4), 322–323.

5. Levin B. M. Time spectra of positron annihilation in neon. *Soviet J. Nucl. Physics*, 1981, v. 34(6), 917–918.

6. Levin B. M. and Shantarovich V. P. Anomalies in the time spectra of positron in gaseous neon. *Soviet J. Nucl. Physics*, 1984, v. 39(6), 855–856.

7. Levin B. M., Kochenda L. M., Markov A. A. and Shantarovich V. P. Time spectra of annihilation of positrons (^{22}Na) in gaseous neon of various isotopic compositions. *Soviet J. Nucl. Physics*, 1987, v. 45(6), 1119–1120.

8. Levin B. M. Orthopositronium: a program for critical experiments. *Soviet J. Nucl. Physics*, 1990, v. 52(2), 342–343.

9. Levin B. M. On the kinematics of one-photon annihilation of orthopositronium. *Phys. At. Nuclei*, 1995, v. 58(2), 332–334.

10. Gidley D. W., Rich A., Sweetman E. and West D. New precision measurements of the decay rates of singlet and triplet positronium. *Phys. Rev. Lett.*, 1982, v. 49, 525–528.

11. Westbrook C.I., Gidley D.W., Conti R.S. and Rich A. New precision measurement of the orthopositronium decay rate: a discrepancy with theory. *Phys. Rev. Lett.*, 1987, v. 58, 1328–1331.

12. Westbrook C. I., Gidley D. W., Conti R. S. and Rich A. Precision measurement of the orthopositronium vacuum decay rate using the gas technique. *Phys. Rev. A*, 1989, v. 40, 5489–5499.

13. Nico J. S., Gidley D. W., Rich A. and Zitzewitz P. W. Precision measurement of the orthopositronium decay rate using the vacuum technique. *Phys. Rev. Lett.*, 1990, v. 65, 1344–1347.

14. Caswell W. E. and Lepage G. P. O(α^2-in-α)-corrections in positronium-hyperfine splitting and decay rate. *Phys. Rev. A*, 1979, v. 20, 36.

15. Adkins G. S. Radiative-corrections to positronium decay. *Ann. Phys. (N.Y.)*, 1983, v. 146, 78.

16. Adkins G. S., Salahuddin A. A. and Schalm K. E. Analytic evaluation of the self-energy and outer-vertex corrections to the decay rate of orthopositronium in the Fried-Yennie gauge. *Phys. Rev. A*, 1992, v. 45, 3333–3335.

17. Adkins G. S., Salahuddin A. A. and Schalm K. E. Order-α corrections to the decay rate of ortopositronium in the Fried-Yennie gauge. *Phys. Rev. A*, 1992, v. 45, 7774–7780.

18. Holdom B. Two U(1)'s and ϵ charge shifts. *Phys. Lett. B*, 1986, v. 166, 196–198.

19. Glashow S. L. Positronium versus the mirror Universe. *Phys. Lett. B*, 1986, v. 167, 35–36.

20. Atoyan G. S., Gninenko S. N., Razin V. I. and Ryabov Yu. V. A search for photonless annihilation of orthopositronium. *Phys. Lett. B*, 1989, v. 220, 317–320.

21. Asai S., Orito S., Sanuki T., Yasuda M. and Yokoi T. Direct search for orthopositronium decay into two photons. *Phys. Rev. Lett.*, 1991, v. 66, 1298–1301.

22. Gidley D. W., Nico J. S. and Skalsey M. Direct search for two-photon modes of orthopositronium. *Phys. Rev. Lett.*, 1991, v. 66, 1302–1305.

23. Al-Ramadhan A. H. and Gidley D. W. New precision measurement of the decay rate of singlet positronium. *Phys. Rev. Lett.*, 1994, v. 72, 1632–1635.

24. Orito S., Yoshimura K., Haga T., Minowa M. and Tsuchiaki M. New limits on exotic two-body decay of orthopositronium. *Phys. Rev. Lett.*, 1989, v. 63, 597–600.

25. Mitsui T., Fujimoto R., Ishisaki Y., Ueda Y., Yamazaki Y., Asai S. and Orito S. Search for invisible decay of orthopositronium. *Phys. Rev. Lett.*, 1993, v. 70, 2265–2268.

26. Skalsey M. and Conti R. S. Search for very weakly interacting, short-lived, C-odd bosons and the orthopositronium decay-rate problem. *Phys. Rev. A*, 1997, v. 55(2), 984.

27. Foot R. and Gninenko S. N. Can the mirror world explain the orthopositronium lifetime puzzle? *Phys. Lett. B*, 2000, v. 480, 171–175.

28. Adkins G. S., Melnikov K. and Yelkhovsky A. Virtual annihilation contribution to orthopositronium rate decay. *Phys. Rev. A*, 1999, v. 60(4), 3306–3307.

29. Asai S., Orito S. and Shinohara N. New measurement of the orthopositronium decay rate. *Phys. Lett. B*, 1995, v. 357, 475–480; Jinnouchi O., Asai S., and Koboyashi T. arXiv: hep-ex/0011011.

30. Karshenboim S. G. Corrections to hyperfine splitting in positronium. *Phys. At. Nuclei*, 1993, v. 56(12), 155–171.

31. Levin B. M. Orthopositronium-lifetime puzzle is not solved: on an effect of non-perturbative contribution. CERN E-Print, EXT-2004-016.