February 2000
UM-P-012-2000

To appear in Physics Letters B



# Can the mirror world explain the ortho-positronium lifetime puzzle?

R. Foot[a*] and S. N. Gninenko[b†]

[a] *Research Centre for High Energy Physics*
*School of Physics*
*University of Melbourne*
*Parkville 3052 Australia*
[b] *CERN, CH-1211 Geneva 23, Switzerland*

Abstract

We suggest that the discrepant lifetime measurements of ortho-positronium can be explained by ortho-positronium oscillations into mirror ortho-positronium. This explanation can be tested in future vacuum experiments.

*Foot@physics.unimelb.edu.au

†Sergei.Gninenko@cern.ch

A "mirror universe" is predicted to exist if parity and/or time reversal are unbroken symmetries of nature [1,2]. The idea is that for each ordinary particle, such as the photon, electron, proton and neutron, there is a corresponding mirror particle, of exactly the same mass as the ordinary particle. The parity symmetry interchanges the ordinary particles with the mirror particles so that the properties of the mirror particles completely mirror those of the ordinary particles. For example the mirror proton and mirror electron are stable and interact with the mirror photon in the same way in which the ordinary proton and electron interacts with the ordinary photons. The mirror particles are not produced in Laboratory experiments just because they couple very weakly to the ordinary particles. In the modern language of gauge theories, the mirror particles are all singlets under the standard $G \equiv SU(3) \otimes SU(2)_L \otimes U(1)_Y$ gauge interactions. Instead the mirror particles interact with a set of mirror gauge particles, so that the gauge symmetry of the theory is doubled, i.e. $G \otimes G$ (the ordinary particles are, of course, singlets under the mirror gauge symmetry) [2]. Parity is conserved because the mirror particles experience $V + A$ (i.e. right-handed) mirror weak interactions while the ordinary particles experience the usual $V - A$ (i.e. left-handed) weak interactions. Ordinary and mirror particles interact with each other predominately by gravity only. At the present time there is some experimental evidence that mirror matter exists coming from cosmology [3] as well as from the neutrino physics anomalies [4].

It was realized some time ago by Glashow [5] that the orthopositronium system provides one sensitive way to search for the mirror universe. The idea is that small kinetic mixing of the ordinary and mirror photons may exist which would mix ordinary and mirror orthopositronium, leading to maximal orthopositronium - mirror orthopositronium oscillations.

The ground state of orthopositronium (o-Ps) decays predominately into 3 photons with a theoretical decay rate computed to be (see e.g. [6] for a review)

$$\begin{aligned}\Gamma &= \frac{2(\pi^2-9)\alpha^6 m_e}{9\pi}\left[1 - 10.28661\frac{\alpha}{\pi} - \frac{\alpha^2}{3}ln\frac{1}{\alpha} + B_0\left(\frac{\alpha}{\pi}\right)^2 - \frac{3\alpha^3}{2\pi}ln^2\frac{1}{\alpha} + \mathcal{O}(\alpha^3 ln\alpha)\right] \\ &\simeq (7.0382 + 3.9\times 10^{-5}B_0)\mu s^{-1}. \qquad (1)\end{aligned}$$

The $B_0$ term parametrizes the non-logarithmic two-loop effects which have yet to be calculated.

On the experimental side, there have been a number of measurements of the lifetime of orthopositronium. The most accurate measurements are given in the table below:

| Reference | $\Gamma_{oPs}(\mu s^{-1})$ | Method | $\Gamma_{coll}$ |
|---|---|---|---|
| Ann Arbor [7] | $7.0482 \pm 0.0016$ | Vacuum Cavity | $\sim (3-10)\Gamma_{oPs}$ |
| Ann Arbor [8] | $7.0514 \pm 0.0014$ | Gas | $\sim 10^3\Gamma_{oPs}$ |
| Tokyo [9] | $7.0398 \pm 0.0029$ | Powder | $\sim 10^4\Gamma_{oPs}$ |

Table Caption: Some measurements of the orthopositronium lifetime. The last column is an estimate of the mean scattering length of the orthopositronium in the experiment.

Comparison of the theoretical prediction with the experimental results suggests a statistically significant discrepancy between the Theory/Tokyo results and the Ann Arbour results. (Note that the $B_0$ term would have to be anomalously large, $\sim 300$, in order to make the theory and the Ann Arbour result agree). Originally it was proposed that an exotic o-Ps decay mode would solve the Theory/Ann Arbor discrepancy. The puzzle seemed so intriguing that even the strongly forbidden decay o-Ps $\to 2\gamma$ was searched for as a candidate for solution. Now, it is believed that practically all possible contributions to the o-Ps decay rate from non-standard annihilation modes are excluded experimentally, for a review see [10] ( and also [9]) and references therein. The purpose of this letter is to see if the oscillations of orthopositronium with its mirror analogue can resolve this discrepancy.

Photon - mirror photon kinetic mixing is described by the interaction Lagrangian density

$$\mathcal{L} = \epsilon F^{\mu\nu} F'_{\mu\nu}, \tag{2}$$

where $F^{\mu\nu}$ ($F'_{\mu\nu}$) is the field strength tensor for electromagnetism (mirror electromagnetism). This type of Lagrangian term is gauge invariant and renormalizable and can exist at tree level [11,2] or maybe induced radiatively in models without $U(1)$ gauge symmetries (such as grand unified theories) [12,5,13]. The effect of ordinary photon - mirror photon kinetic mixing is to give the mirror charged particles a small electric charge [12,5,2]. That is, they couple to ordinary photons with charge $2\epsilon e$‡.

Orthopositronium is connected via a one-photon annihilation diagram to its mirror version (o-Ps') [5]. This breaks the degeneracy between o-Ps and o-Ps' so that the vacuum energy eigenstates are (o-Ps + o-Ps')$/\sqrt{2}$ and (o-Ps - o-Ps')$/\sqrt{2}$, which are split in energy by $\Delta E = 2h\epsilon f$, where $f = 8.7 \times 10^4$ MHz is the contribution to the ortho-para splitting from the one-photon annihilation diagram involving o-Ps [5]. Thus the interaction eigenstates are maximal combinations of mass eigenstates which implies that o-Ps oscillates into o-Ps' with probability:

$$P(\mathrm{o-Ps} \to \mathrm{o-Ps'}) = \sin^2 \omega t, \tag{3}$$

where $\omega = 2\pi\epsilon f$. Note that the probability $P(\mathrm{o-Ps} \to \mathrm{o-Ps'})$ can, in principle, also be affected by an additional splitting of o-Ps and o-Ps' states by an external electric or magnetic field [15].

Let us first review the simplest case of o-Ps $\to$ o-Ps' oscillations in vacuum [5]. In this case, because the mirror decays are not detected, this leads to an *apparent* increase in the decay rate, since the number of o-Ps, $N$ satisfies

$$N = \cos^2 wt e^{-\Gamma^{sm} t} \simeq exp[-t(\Gamma^{sm} + w^2 t)], \tag{4}$$

where $\Gamma^{sm}$ is the standard model decay rate of o-Ps (i.e. when the oscillation length goes to infinity). Thus $\Gamma^{eff} \approx \Gamma^{sm} + w^2/\Gamma^{sm}$.

‡Note that the direct experimental bound on $\epsilon$ from searches for 'milli-charged' particles is $\epsilon \lesssim 10^{-5}$ [14].

Actually the above computation is not applicable to any of the experiments listed in the table because in each case the collision rate is larger than the decay rate and loss of coherence due to the collisions must be included [15].

Observe that there is the interesting possibility that two different experiments could get different values for the lifetime because of the different collision rates of the orthopositronium. It is well known that collisions damp the oscillations and in the limit where the collision rate is much larger than the decay rate (or oscillation frequency; whichever is smaller) the effect of the oscillations becomes negligible (Quantum Zeno effect). Let us assume for now that the theory computation is accurate (i.e. the unknown quantity $B_0$ is not anomolously large). The agreement with the Tokyo experiment can be explained because of the very large collision rate of the orthopositronium in the powder. However because of the two different collision rates of the two Ann Arbour experiments, they cannot both be explained. Interestingly, some doubts about the Ann Arbour gas experiment have emerged due to the fact that the thermalization time of o-Ps (time of slowing of the orthopositronium atoms by collisions in matter) needs to be taken into account for a precision measurement of the o-Ps decay rate, see e.g. [9], [16], [17]. If the o-Ps atoms are not completely thermalized, they are moving faster and their decay rate is spuriously higher because of the higher pickoff annihilation rate. This could result in a systematic error in the determination of $\Gamma_{oPs}$. A similar conclusion has been drawn in a recent paper of Skalsey et al. [18], where it is claimed that at the lowest pressures used in the gas measurements [8] o-Ps were indeed not completely thermalized. This is crutial, since the Ann Arbor team used the asymptotic o-Ps decay rate extrapolated from low-pressure measurements. The size of the correction on the o-Ps decay rate due to incomplete thermalization still has to be determined.

If we ignore this gas result then the discrepancy between the theory/Tokyo results and the Ann Arbour vacuum cavity experiment can be explained by the orthopositronium-mirror orthopositronium oscillation mechanism. To see how this works in detail we need to consider the case where $\Gamma_{coll} \gg \Gamma^{sm}$, then the evolution of the number of orthopositronium states, $N$, satisfies:

$$\frac{dN}{dt} \simeq -\Gamma^{sm} N - \Gamma_{coll} N \rho, \tag{5}$$

where the second term is the rate at which o-Ps oscillates into o-Ps' (whose subsequent decays are not detected). In this term, $\rho$ denotes the average of oscillation probability over the collision time. That is,

$$\rho \equiv \Gamma_{coll} \int_0^t e^{-\Gamma_{coll} t'} \sin^2 wt' dt' \simeq \Gamma_{coll} \int_0^t e^{-\Gamma_{coll} t'} (wt')^2 dt', \tag{6}$$

where we have used the constraint that the oscillation probability is small, i.e. $wt \ll 1$ (which must be the case given that the discrepancy between say the vacuum cavity experiment and Tokyo experiment is less than 1 percent). So long as $t \gg 1/\Gamma_{coll}$ (which is an excellent approximation for the gas and powder experiments and a reasonable one for the vacuum cavity experiment) then

$$\rho \simeq \frac{2w^2}{\Gamma_{coll}^2}. \tag{7}$$

Thus substituting the above equation into Eq.(5) we have

$$\Gamma^{eff} \simeq \Gamma^{sm} + \frac{2w^2}{\Gamma_{coll}} = \Gamma^{sm}\left(1 + \frac{2w^2}{\Gamma_{coll}\Gamma^{sm}}\right). \quad (8)$$

Thus the high decay rate measured in the vacuum cavity experiment relative to the theory result can be explained provied that

$$\frac{2w^2}{\Gamma_{coll}\Gamma^{sm}} \simeq 0.0014 \pm 0.0002. \quad (9)$$

The experiment involves a range of cavity sizes where the decay rate is obtained by extrapolation to an infinite volume. From Ref. [7] we estimate that the largest cavity corresponds to $\Gamma_{coll} \sim 3\Gamma_{oPs}$, which, neglecting the contribution from external fields (which are in fact negligible in this case [15]), implies that

$$w^2 \sim 2 \times 10^{-3}\Gamma_{oPs}^2 \Rightarrow \epsilon \simeq (5 \pm 1) \times 10^{-7}. \quad (10)$$

The much larger collision rates of the Tokyo (and gas) experiments means that the oscillations can have no effect on these experiments. Thus the high value of the vacuum experiment relative to the theory/Tokyo results can be explained. However the high value of the Michigan gas experiment cannot be explained by oscillations but is presumably due to larger than expected systematic errors (as discussed earlier).

Interestingly the value of $\epsilon$ identified in Eq.(10) is consistent with all known experimental and cosmological bounds (including SN1987) with the exception of the big bang nucleosynthesis bound (see figure 1 of Ref. [19] for a review and references). Big bang nucleosynthesis suggests the bound [20] $\epsilon \lesssim 3 \times 10^{-8}$. Thus, if it were experimentally proven that $\epsilon$ is as large as Eq.(10) then it would presumably mean that some of the assumptions of big bang nucleosynthesis would have to be modified.

The experimental signature of the o-Ps → o-Ps' oscillations is the 'disappearance' of an energy deposition of $\sim 1$ MeV, which is expected from the ordinary o-Ps annihilation in a $4\pi$ calorimeter surrounding the o-Ps formation region, i.e. an invisible decay of o-Ps. The first experiment on such decays was performed a long time ago [21], and then repeated with higher sensitivity [22]. The results exclude contributions to the o-Ps decay rate from invisible decay modes (such as o-Ps→ $\nu\nu$, millicharged particles, etc..) at the level of BR(o-Ps→ *invisible*) $< 3 \cdot 10^{-6}$, but are not very sensitive to the o-Ps → o-Ps' oscillation mechanism because of the high collision rate in these experiments. Indeed the limit on $\epsilon$ extracted from the results of ref. [22], taking into account the suppression collision factor, is $\epsilon < 10^{-6}$ [15] and is not strong enough to exclude a possible mirror contribution given by Eqs.(8,10) to the o-Ps decay rate. Thus, a vacuum experiment with significantly higher sensitivity will be necessary to confirm or rule out the mirror world effect. The best approach would be to combine the lifetime and invisible decay rate measurements in a single cavity experiment. In this case one would have a good cross-check: the higher o-Ps decay rate the larger peak at zero energy.

If the photon - mirror photon mixing is as large as suggested here then there will be a number of interesting implications. For example, any mirror matter in the center of the sun can become quite hot due to the absorption of ordinary photons. The subsequent radiation of mirror photons by the mirror matter would be absorbed by the surrounding ordinary matter providing a new source of energy transport in the solar interior. Another implication of the large photon - mirror photon kinetic mixing is that it may be large enough (depending on the chemical composition of the mirror planet) to make mirror planets opaque to ordinary photons. Thus the recent observations [23] of a transit of the extrasolar planet HD 209458 does not exclude the hypothesis [24] that the close-in extrasolar planets are mirror planets. The remaining prediction of the mirror extrasolar planet hypothesis is that they cannot reflect the light from the star (i.e. their albedo is essentially zero). This prediction is currently being tested [25]. The photon - mirror photon kinetic mixing may provide a useful way of observing a mirror supernova explosion. This is because the rapid conversion of mirror matter into ordinary matter (via $e'^+e'^- \to e^+e^- \to \gamma + \gamma$) may provide a burst of ordinary light. Indeed it may be possible that this is the mechanism which can realize Blinnikov's proposal [26] that gamma ray bursts are infact collapsing (or merging) mirror stars. Finally, it is interesting to note that composites of mirror matter with no net mirror charge will exert small Van der Waals forces upon ordinary matter, possibly making terrestrial encounters with cosmic chunks of mirror matter also observable [5], [27]. Indeed the collision of a mirror object (e.g. mirror asteroid) with the earth may well be a health hazard as the mirror object will not burn up in the atmosphere, but may nevertheless deposit a large amount of energy when it hits the surface as the object losses energy due to electromagnetic interactions induced by the kinetic mixing. Such an impact would not be expected to leave any significant crater. [§].

While it is fun to speculate about the effects of large photon - mirror photon kinetic mixing, real progress requires experiments. Given the already strong evidence for the mirror world coming from dark matter [3] and the neutrino physics anomalies [4] (as well as the intuitive expectation that nature should be left-right symmetric) it is obviously important to experimentally determine whether the orthopositronium lifetime puzzle is one more window on the mirror world. We hope that future experiments will shed light on this issue [28].

## Note Added

After completion of this paper the preprint [29] appeared which calculates the unknown $B_0$ term in Eq.(1). They obtain the value $B_0 \simeq 44$ which gives a theoretical orthopositronium decay rate of $\Gamma = 7.0399\ \mu s^{-1}$ [29]. Thus, the theoretical calculation agrees with the Tokyo experiment which we in fact anticipated in this paper. The theoretical calculation is about 5 standard deviations below the vacuum cavity experiment, which in our paper is explained by the influence of the mirror universe.

---

[§] It is of course amuzing to speculate that the 1908 Tunguska event may have been one such event since no impact crater was ever found.

**Asknowledgments**

S.G. would like to thank S. Glashow for stimulating interest and valuable discussions and S. Asai for communications on o-Ps thermalization. R.F. thanks S. Blinnikov, Z. Silagadze and R. Volkas for discussions/correspondence. R.F. is an Australian Research Fellow.

# REFERENCES


[1] T. D. Lee and C. N. Yang, Phys. Rev. 104, 256 (1956); I. Kobzarev, L. Okun and I. Pomeranchuk, Sov. J. Nucl. Phys. 3, 837 (1966); M. Pavsic, Int. J. Theor. Phys. 9, 229 (1974).

[2] R. Foot, H. Lew and R. R. Volkas, Phys. Lett. B272, 67 (1991).

[3] S. I. Blinnikov and M. Yu. Khlopov, Sov. J. Nucl. Phys. 36, 472 (1982); Sov. Astron. 27, 371 (1983); E. W. Kolb, M. Seckel and M. S. Turner, Nature 514, 415 (1985); M. Yu. Khlopov et al, Soviet Astronomy, 35, 21 (1991); M. Hodges Phys. Rev. D47, 456 (1993); Z. G. Berezhiani, A. Dolgov and R. N. Mohapatra, Phys. Lett. B375, 26 (1996); Z. G. Berezhiani, Acta Phys. Polon. B27, 1503 (1996); Z. Silagadze, Phys. At. Nucl. 60, 272 (1997); hep-ph/9908208; S. Blinnikov, astro-ph/9801015; astro-ph/9902305; astro-ph/9911138. G. Matsas et al., hep-ph/9810456; N. F. Bell and R. R. Volkas, Phys. Rev. D59, 107301 (1999); R. Foot, Phys. Lett. B452, 83 (1999); R. Mohapatra and V. Teplitz, astro-ph/9902085; R. Foot and R. R. Volkas, Phys. Rev. D61, 043507 (2000); Astroparticle Phys. 7, 283 (1997); R. R. Volkas and Y. Y. Y. Wong, hep-ph/9907161; V. Berezinsky and A. Vilenkin, hep-ph/9908257.

[4] R. Foot, H. Lew and R. R. Volkas, Mod. Phys. Lett. A7, 2567 (1992); R. Foot, Mod. Phys. Lett. A9, 169 (1994); R. Foot and R. R. Volkas, Phys. Rev. D52, 6595 (1995).

[5] S. L. Glashow, Phys. Lett. B167, 35 (1986).

[6] A. Czarnecki and S. G. Karshenboim, hep-ph/9911410.

[7] J. S. Nico, D. W. Gidley, A. Rich, and P. W. Zitzewitz, Phys. Rev. Lett. 65, 1344 (1990).

[8] C. I. Westbrook, D. W. Gidley, R. S. Conti and A. Rich, Phys. Rev. A40, 5489 (1989).

[9] S. Asai, S. Orito and N. Shinohara, Phys. Lett. B357, 475 (1995).

[10] M. I. Dobroliubov, S. N. Gninenko, A. Yu. Ignatiev and V. A. Matveev, Int. Journ. Mod. Phys. A8, 2859 (1993).

[11] R. Foot and X-G. He, Phys. Lett. B267, 509 (1991).

[12] B. Holdom, Phys. Lett. B166, 196 (1985).

[13] M. Collie and R. Foot, Phys. Lett. B432, 134 (1998).

[14] A. A. Prinz et al., Phys. Rev. Lett. 81, 1175 (1998).

[15] S. N. Gninenko, Phys. Lett. B326, 317 (1994).

[16] T. Chang, M. Xu and Z. Zeng, Phys. Lett. A126, 189 (1987).

[17] S. Asai, Ph.D. thesis, Univ. of Tokyo, ICEPP Report UT-ICEPP 94-08 (1994).

[18] M. Skalsey et al., Phys. Rev. Lett. 80, 3727 (1998).

[19] S. Davidson, S. Hannestad and G. Raffelt, hep-ph/0001179.

[20] E. D. Carlson and S. L. Glashow, Phys. Lett. B193, 168 (1987).

[21] G. S. Atojan, S. N. Gninenko, V. I. Razin and Yu. V. Ryabov, Phys. Lett. B220, 317 (1989).

[22] T. Mitsui et al., Phys. Rev. Lett. 70, 2265 (1993).

[23] D. Charbonneau et al, ApJ, 529, L45 (2000); G. W. Henry et al, ApJ, 529, L41 (2000).

[24] R. Foot, Phys. Lett. B471, 191 (2000).

[25] D. Charbonneau and R. W. Noyes, astro-ph/0002489.

[26] S. Blinnikov, astro-ph/9902305; astro-ph/9911138.

[27] A. De Rujula and S. L. Glashow, Nature 312 (1984) 734.

[28] See, for example, I. N. Meshkov, Phys. Atom. Nucl. 61, 1679 (1998); Yad. Fiz. 61, 1796 (1998).
[29] G. S. Adkins, R. N. Fell and J. Sapirstein, hep-ph/0003028.