Positronium Portal to the Mirror World

Paolo Crivelli[1]

[1]ETH Zurich, Institute for Particle Physics, 8093 Zurich, Switzerland

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It was realized sometime ago by Glashow that the mirror matter could have a portal to our world through photon-mirror photon mixing (ϵ) which would lead to orthopositronium (oPs) to mirror orthopositronium oscillations. This would result in a modification of the oPs decay rate however this effect is too small to be observed. Another experimental signature of this process is the apparently invisible decay of oPs. In this paper, we describe an experiment to search for the decay oPs$\rightarrow$invisible in a vacuum cavity with an expected sensitivity in the mixing strength of $\epsilon \simeq 10^{-9}$. This is more than one order of magnitude below the current Big Bang Nucleosynthesis limit and it is in a region of parameter space of great theoretical and phenomenological interest. An experiment with such a sensitivity is particularly timely in light of the recent claims for the observations of the annual modulation signal consistent with a mirror type dark matter interpretation.

1 Introduction

Cosmological observations of galactic rotational curves [1] and the gravitational lensing [2, 3] give strong evidence for the existence of dark matter [4]. This is one of the strongest indications for the existence of new physics beyond the standard model because within this theory no candidates can be found, thus, the identification of the origin of dark matter is a task of enormous importance for both particle physics and cosmology. At present, the most popular candidates for the (thermal-produced) dark matter are the so-called weakly interacting massive particles (WIMPs), which are e.g. lightest supersymmetric particles, Kaluza-Klein particles in universal extra dimension models or axions. However, despite of significant efforts the experiments looking for WIMPs lead so far to negative results, thus, pushing further possible WIMPs searches into higher energy and/or higher sensitivity frontiers. The confirmation by the DAMA/LIBRA experiment [5] of the annual modulation signal observed by the DAMA/NaI [6] could potentially be the first direct terrestrial experimental detection of the existence of non-baryonic dark matter in our galactic halo. Very recently, also the CoGeNT collaboration [7] claimed the observation of a modulation and the CRESST-II experiment reported more than 4 sigma excess of events above their expected background [8]. However, standard WIMPs cannot explain these observations. A possibility is to conclude that those observations are originated by poorly understood background. Another approach is to look for a different model that could explain these results. Among numerous alternatives that have been discussed, one of the most promising, which could reconcile the DAMA and CoGeNT annual modulation signals, the CRESST excess and the negative results of higher thresholds experiments [9]-[11], is mirror type dark matter [12]-[14]. Mirror matter is an exact copy of the ordinary matter (e.g the mirror electron would have the same mass of the electron) with the same physics (i.e. the same couplings) but in this model the particles have the left and right chiral properties interchanged. Therefore, if mirror matter is present in our universe it would mean that parity (spatial-inversion) is an unbroken symmetry of nature. Mirror baryons are naturally dark, stable and massive. Currently, it seems that this concept could also explain in a natural way the visible and dark matter densities in the universe ($\Omega_B = 0.044$ and $\Omega_{DM} = 0.26$) [15, 16]. The mirror matter, in addition to gravity, could communicate with our world through photon-mirror photon kinetic mixing (with strength ϵ) [17] or the Higgs- mirror Higgs quartic couple $\lambda\phi\phi^\dagger\phi'\phi'^\dagger$ [18, 19][1]. These are the only renormalizable and gauge invariant terms that can be added to the standard model Lagrangian.

2 Experimental technique and setup

The experiment presented here is based on the ETHZ slow positron beam to form Ps in a vacuum cavity combined with the BGO calorimeter used in our previous search for $Ps \rightarrow invisible$ decays [21] with a modified geometry to accommodate the beam pipe [22, 23]. The photon mirror-photon kinetic mixing would break the degeneracy between Ps and Ps' so that the vacuum energy eigenstates are a linear combination of the mass eigenstates (Ps $\pm$ Ps')$/\sqrt{2}$. This would lead to orthopositronium to mirror orthopositronium Rabi oscillations [24]. The experimental signature of this process is the apparently invisible decay of Ps. By invisible is meant that the energy $2m_e$ expected for ordinary decays is not detected in a hermetic calorimeter surrounding the Ps formation target. Therefore, the occurrence of the Ps$\rightarrow$Ps'$\rightarrow$invisible conversion would appear as an excess of events with zero-energy deposition in the calorimeter above those expected either from Monte Carlo prediction of the background or from direct background measurements. Compared to our previous search for Ps$\rightarrow$invisible this experiment present many advantages. A factor 10^2 more statistics can be collected with the same number of positrons because of the much more efficient trigger system, a gain of almost a factor 10 in the fraction of Ps atoms produced per impinging positron (this concomitantly reduces the background from 2 photons annihilations) and a higher efficiency for signal detection. Furthermore, because the number of collisions per lifetime (N_{coll}) of the Ps with the cavity walls affects the coherence of oscillation [25], the probability of oscillation ($\sim \sqrt{N_{coll}}$) will be about 100 times higher than in the previous search where Ps was produced and confined in the pores of an aerogel target ($N_{coll} \sim 10^4$) instead of a vacuum cavity ($N_{coll} \sim 1$) as proposed here. Another great advantage is the fact that the number of collisions is an experimental parameter that can be tuned taking runs at different positron implantation energies. From 3 to 5 keV the mean velocity of the created Ps increases by about a factor of two, thus, the collision rate with the walls is 2 times bigger and the signal is suppressed by the same factor. This without affecting the background level since the fraction of Ps will just vary by a few % [26]. However, compared to the previous experiment, there is a clear disadvantage: the calorimeter must be mounted outside the vacuum chamber so that the vacuum pipe introduces a loss of the photon energy.

[1]This may result in dramatic consequences for the LHC, making the significance of the Higgs signal lower due to decreasing of the *Signal/Background* ratio if the mass splitting is large compared to the Higgs LHC experiments mass resolution [20].

3 Expected background level and sensitivity

In Table 1, we summarize the estimated contributions of the expected background sources of the experiment. The main contribution to the first background is coming from the losses of annihilation energy coming in the vacuum beam pipe. This was estimated with the help of the simulation using a beam pipe made of 0.04 mm aluminum and 0.80 mm thick carbon (similar to the one produced at ETHZ that was used at the H1 experiment at DESY). The target substrate and the copper wire surrounding the beam pipe were also included. We will investigate other possibilities, e.g to use an “active” beam pipe in which the energy lost by the photons is measured. This could be a scintillating crystal with a bore to be used as a vacuum cavity with an internal coating compatible with a good vacuum. The most dangerous background source is due to the backscattered positrons, either from the carbon foil or from the target. A possible way to further suppress this background is the installation of an electrode to which a pulsed voltage is applied in order to redirect back the positrons in the target avoiding them to escape detection region [22].

	BACKGROUND SOURCE	expected
1)	Photon detection loss:	$\simeq 10^{-8}$
2)	Positron backscattered from carbon foil	$< 10^{-7}$
3)	Positron Backscattered from SiO2	$< 10^{-7}$
4)	Fast Ps from carbon foil	$< 5 \times 10^{-8}$
5)	Fast Ps from target	$<< 10^{-8}$

Table 1: *Summary of the expected background level for the different background sources.*

The sensitivity of the experiment is defined as the level at which the first background event is expected:

$$S_{\text{Ps}\to\text{invisible}} = 1/(N_{\text{Ps}} \cdot \epsilon_{tot}) \quad (1)$$

where the terms in the denominator are the integrated number of produced Ps (N_{Ps}) and $\epsilon_{tot} \simeq 0.95$ is the total efficiency to detect an invisible decay. The losses in signal efficiency of about 4.5% arise from the possibility of having 2 or more positrons per bunch. We estimated the rate of these events using $R_{2e^+} = 2 \cdot \tau_{bunch} \cdot R_{e^+}$ where $\tau_{bunch} = 300$ ns and $R_{e^+} = 7.5 \times 10^4/s$ is the number of delivered positrons per second on the target in continuous mode. For two or more positrons there is always annihilation energy deposition in the ECAL, hence this effect does not result in a background. The number of Ps/s, R_{Ps}, is defined as a product

$$R_{\text{Ps}} = R_{e^+} \cdot \epsilon_{\text{Ps}} \cdot \epsilon_{tagging} \cdot \epsilon_{Bunching} \quad (2)$$

where the first factor was defined above, the second one is the efficiency for Ps production (about 30%), the third one $\epsilon_{tagging} = 0.04$ is the efficiency of the tagging system and the last one, $\epsilon_{Bunching} = 0.1$, are the losses due to the duty cycle of the bunching system. As in our previous search, the length of the gate for the ADCs has to be at least 3 μs in order to suppress the probability for Ps to decay after this time to a level of 10^{-9}. Therefore, a limit on the branching ratio of 4×10^{-8}, which is 10 times more stringent than the current one[2], can be reached in less than a 8 days run ($\approx 6 \times 10^7$ observed Ps annihilations). Assuming

[2]For comparison, it took us 6 months of data taking to set the current limit.

that the DAMA/LIBRA and the CoGeNT annual signal modulations and the CRESST excess are generated by elastic scattering of mirror matter, the mixing strength should of the order of $\epsilon \simeq 10^{-9}$ [14]. With the estimated average number of Ps collisions in the vacuum cavity we plan to use $N_{coll} \simeq 0.5$ (for 5 keV implantation energy of the positrons), the expected branching ratio for this process will be $Br(\text{Ps} \to \text{invisible}) \simeq 5 \times 10^{-8}$ (we assume $\epsilon = 2 \times 10^{-9}$ for the following estimation), thus, a total number of $\simeq 35$ signal events would be detected in the ECAL during 3 months of data taking. We are expecting a background level comparable with the signal rate, thus, about the same amount of background events are expected which means that a discovery with about 6 σ significance is possible. As explained above, a unique feature of our proposal is the possibility to change the experimental conditions (i.e. the number of the Ps collisions with matter), and hence to cross check the results without affecting the background. For an implantation energy of the positrons of 3 keV, the number of excess events will be 2 times smaller compared to 5 keV positrons.

4 Conclusions

The proposed experiment to search for invisible decays of positronium is designed with the goal to confront directly the interpretation of the dark matter direct searches in terms of mirror dark matter. In case of a signal detection, this will prove unambiguously that dark matter should be identified with mirror matter solving this very important problem of cosmology and particle physics. Furthermore, the value of the coupling (ϵ) of matter to their mirror counterpart via photon mirror-photon kinetic mixing will be precisely determined. In case that no signal will be observed, this measurement will exclude that the DAMA/LIBRA and CoGeNT annual signal modulation is generated by elastic scattering of mirror matter in their detectors and will provide an improvement of more than a factor of 10 on the branching ratio for Ps→invisible. This will place stringent limits for possible new physics beyond the standard model like for example extra-dimensions, milli-charged particles and hidden sectors.

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