Study of the Formation and Decay of Positronium by Bombarding Differently Doped Aerogel Targets with High energy Positron beams

Team name:

The Positronium Pioneers

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Submission to Beamline for Schools competition

1. Why we want to go

Facilities like CERN and DESY are epicentres of progress in modern-day particle physics, and for budding physicists like us, the Beamline for Schools competition provides a magnificent platform for broadening our horizons on the experimental side of things.

Most high school physics curricula are restricted mostly to classical physics with barely any modern physics. However, all of us are deeply interested in learning particle physics. The opportunity to work with the best scientific minds using state-of-the-art equipment is invaluable for us. Furthermore, conducting this experiment at CERN or DESY would give us a tremendous boost in our journey to becoming future physicists.

2. Why we chose our experiment

Our chosen topic of measuring the differences in lifetimes of positronium in various media, particularly gas-doped aerogels, aligns perfectly with our interests and the objectives of the competition. Positronium, the bound state of an electron and a positron, is a fascinating system that can provide valuable insights into the properties of materials and also the matter-antimatter annihilation process. By exploring how the positronium lifetime is affected by the electron environment and porous structure of different aerogel samples, we hope to uncover new knowledge that can be applied in areas such as cosmology, material science, condensed matter physics, and medical imaging.

3. Theory

Positronium is a quasi-stable neutral bound state of an electron and a positron. The formation of positronium involves the capture of one of the target electrons by an incident positron, to form the bound state Ps. This has drawn significant attention as it is experimentally and theoretically one of the simplest examples of a rearrangement collision.

Positronium can exist in the two spin states, $S = 0, 1$. The singlet state ($S = 0$), in which the electron and positron spins are antiparallel, is termed para-positronium (p-Ps), whereas the triplet state ($S = 1$) is termed ortho-positronium (o-Ps). The spin state has a significant influence on the energy level structure of the positronium, and also on its lifetime against self-annihilation.

It is expected from spin statistics that generally, positronium will be formed with a population ratio of ortho- to para-equal to 3:1, and eventually most of the ortho Ps formed will annihilate in this state, considering absence of any significant quenching.

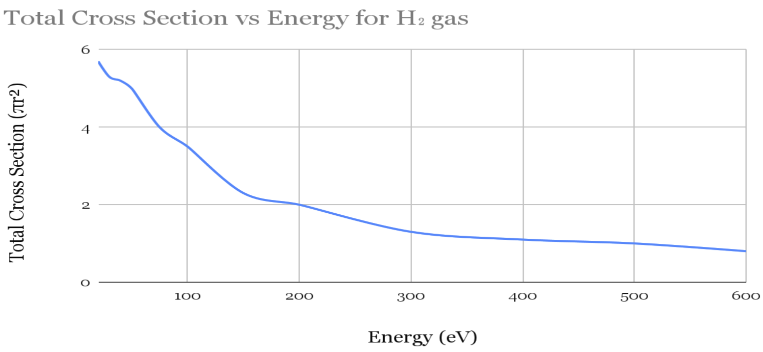
Experiments indicate that due to o-Ps significantly longer lifetime than p-Ps, it is easier to measure their lifetime. For ground state positronium with L = 0, annihilation of the singlet ($^1S_0$) and triplet ($^3S_1$) spin states can only proceed by the emission of even and odd numbers of photons respectively. Thus, in the absence of any perturbation the annihilation of para-Ps proceeds by the emission of two, four etc. gamma-rays, and the annihilation of ortho-Ps by the emission of three gamma-rays

4. Synopsis

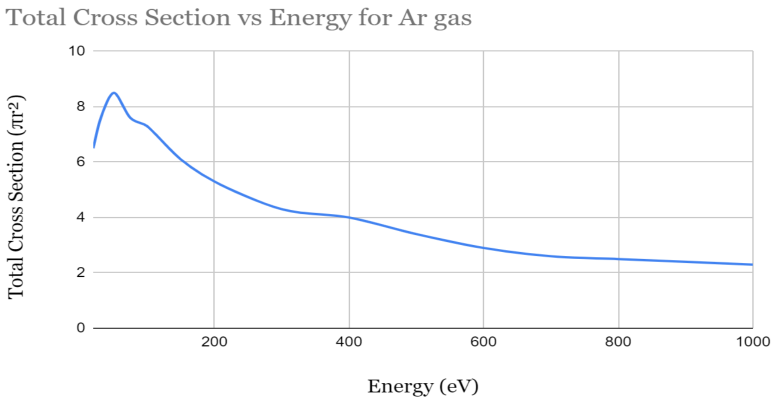
We plan to study the differences in the lifetime of positronium formed within different media i.e. Hydrogen gas, Nitrogen gas, and Argon gas. Most experiments in the past involving positronium have been done by using slow positron beams from a radioactive source (most commonly Na_{22}). This is because higher energy positron beams decrease the cross section for positronium formation. However, we want to use the high-energy positron beams available at CERN or DESY because of three reasons:

1) Firstly, as pointed out by Benjamin Rienacker, the physics coordinator of AEgIS, in his master's thesis, "Unfortunately positrons emitted from radioactive sources have broad energy and large angular distributions which make them useless for most experimental setups." Using positron beams available at CERN or DESY alleviates the issue, offering control over energy and flux (narrowed) without the use of radioactive sources like Na_{22}.
2) Secondly, very high-energy positron beams have not been employed in positronium experiments, sparking our curiosity to explore this unexplored domain. According to Graph 1, the highest energies of positron beams that have been used to produce positronium for hydrogen gas, argon gas, and nitrogen gas are respectively 600 eV, 1000 eV, and 32 eV.
3) Moreover, high-energy beams could offer insights into matter-antimatter asymmetry. The standard model lacks conclusive evidence to explain the observed disparity in matter and antimatter post-Big Bang in the early universe. Slow positron beams, not reflecting post-Big Bang conditions, hinder our understanding of positronium's significance during this epoch. Although our 1 GeV energy beam we are using does not exactly simulate the Big Bang conditions, its energy would still be higher than any experiment conducted on positronium so far and could possibly give us more insights into the matter-antimatter asymmetry.

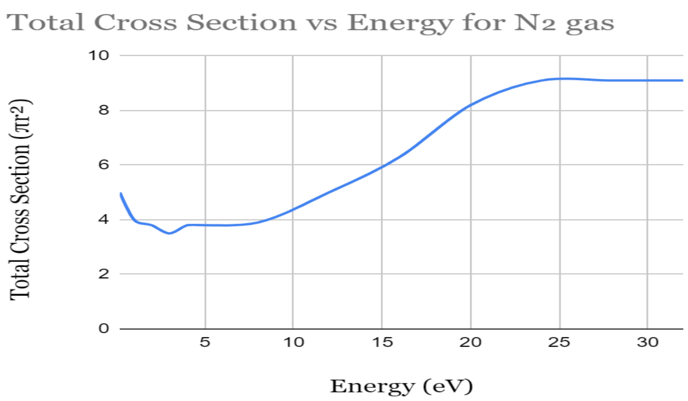
We can see that the Graph for Hydrogen shows an expected trend, the cross-section decreases as the energy increases, whereas in the Argon graph, the cross-section first peaks at around 50 eV and then starts declining. We can see that Nitrogen goes to a minimum around 3 eV and then increases till it becomes constant around 25 eV. Despite the lack of data for all the gases at high energies we can extrapolate and predict what might happen at high energies using these graphs. The data for these graphs has been taken from the citations (1, 2, 3, 4, 7, 8, 9, 10, 11, 12, 13 and 15).



Graph 1(a)



Graph 1(b)



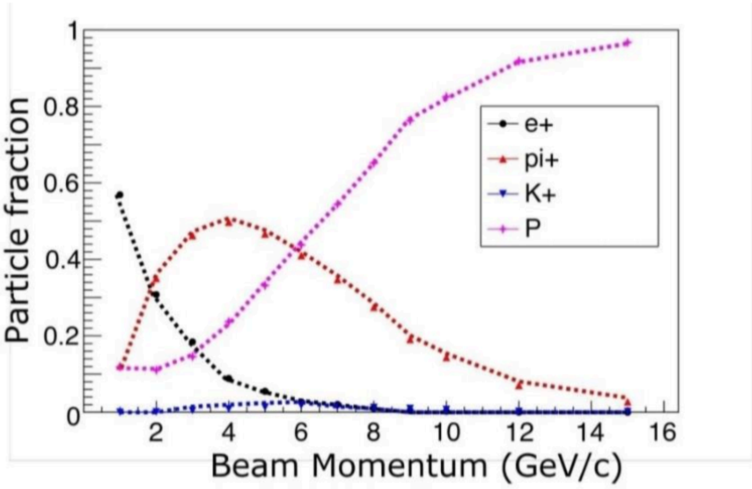
Graph 1(c)

Graph 1: Cross Section versus Energy Graphs for (a) Hydrogen Gas (b) Argon Gas (c) Nitrogen Gas

5. Experimental Procedure

5.1 Beam Calibration:

A positronium consists of an electron and positron. The electrons would be present in the target material. However, for the positron we plan to use the beams. For our experiment, the T9 beam's momentum should be 1 GeV/c. This is because the maximum flux of positrons occurs at this particular momentum (Graph 2). This would ensure the maximum number of positrons in the beam and thus maximise the chances of positronium formation. However, in DESY, we would have access to a pure positron beam. Thus, we would not have to worry about the flux of positrons and can use a beam of momentum 1 GeV/c.



Graph 2: Flux of different positive particles in T9 beam at different velocities.

5.2 Target Preparation:

We plan to use an aerogel Silicon Dioxide (SiO_2) doped with different gases for this experiment. The aerogel has intergranular spaces that have a relatively low electron density; this increases the chances that the ortho-positronium formed would self-decay into three photons. We would also ignore any effect that the high-energy beam would have on the aerogel. The gases we plan to use are Nitrogen, Argon, and Hydrogen gas. Nitrogen has most commonly been used in past experiments, Argon is an inert gas, and Hydrogen can be ionised more easily than Argon.

Gas	Hydrogen	Argon	Nitrogen
Ionisation Energy	1312 kJ/mol	1521 kJ/mol	1503 kJ/mol

Ionisation energy (I.E.) refers to the energy required for an isolated gaseous atom to release an electron. Given that argon's I.E. is considerably higher than hydrogen, we predict that more ortho-positronium would self-decay instead of picking off external electrons in argon doped aerogel, indicating a higher lifetime.

Formation of the aerogel:
Nitrogen: This aerogel is produced by incorporating nitrogen-containing compounds into the aerogel matrix during the synthesis process.
Hydrogen: Hydrogen-doped aerogels are produced by incorporating hydrogen-containing compounds into the aerogel matrix during the synthesis process.
Argon: Argon-doped aerogels are produced by incorporating argon gas into the porous structure of the aerogel during the synthesis process.

5.3 Experimental Setup:

The setup consists of an array of scintillators surrounding the Aerogel target, as depicted below:

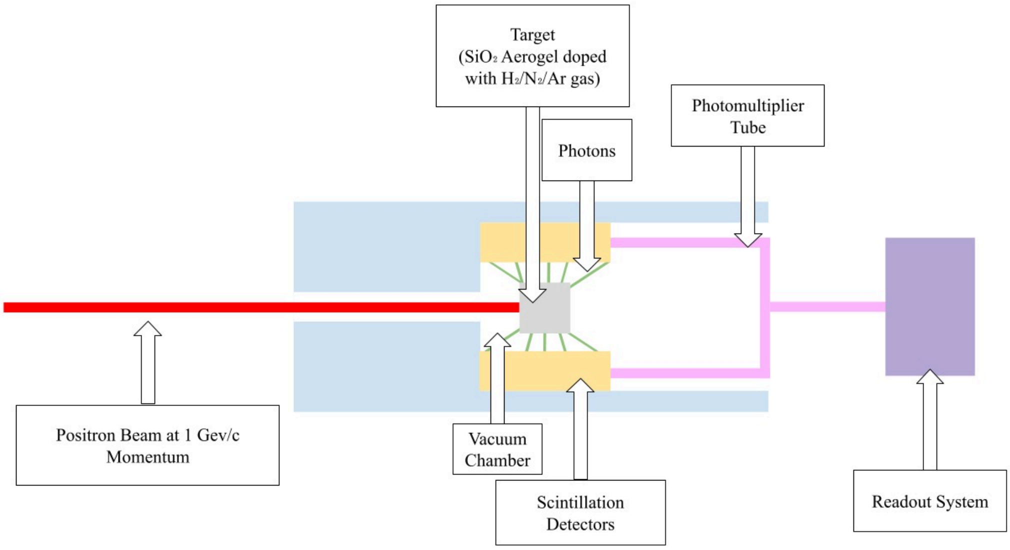


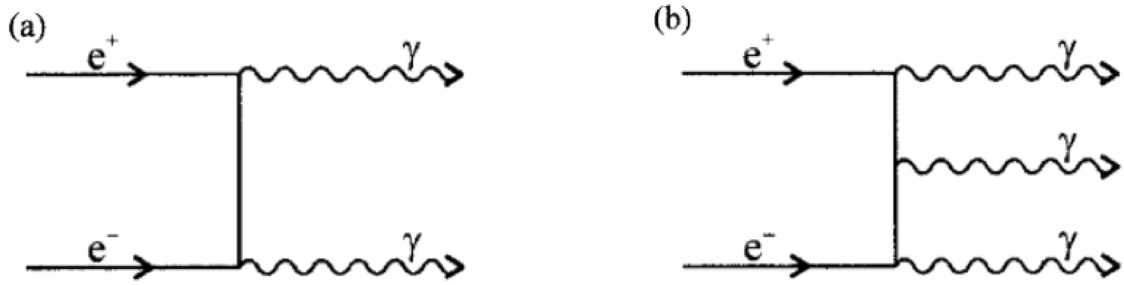
Figure 1: Schematic diagram of experimental set-up.

5.4 Detection:

For detecting the ortho-positronium, we plan to use triple coincidence of scintillators. Outside the collision chamber, multiple scintillators would be placed surrounding the target. During collision, one of these three phenomena could occur:

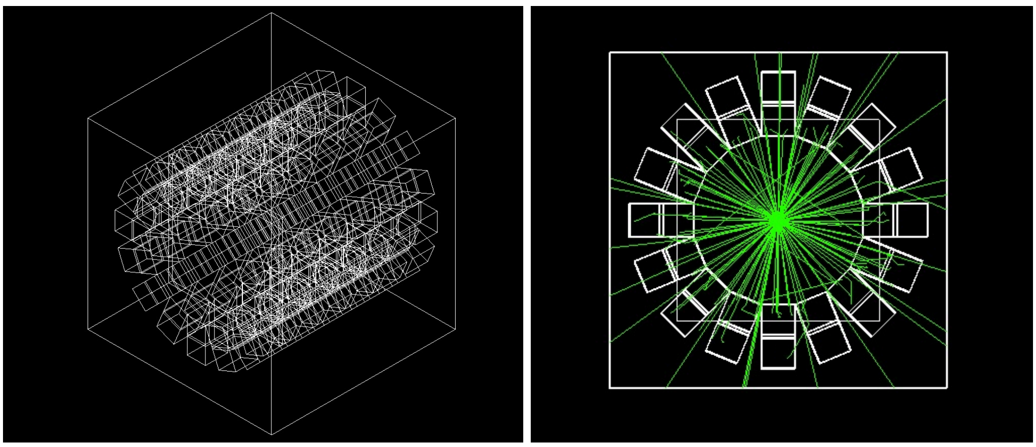
a) Direct electron-positron annihilation releasing two photons (gamma rays)
b) Formation of para-positronium releasing two photons (gamma rays)
c) Formation of ortho-positronium releasing three or other odd numbers of photons (except one)

When the ortho-positronium decomposes (self-annihilates), three photons would be released simultaneously. Thus, the detection of three photons with negligible time delays (virtually undetectable by our scintillators) indicates that ortho-positronium had been formed. This detection strategy is commonly used in ortho-positronium detection experiments. One example was shown in a paper by D Bosnar in 2015 which was also studying three gamma ray annihilations of positronium (D Bosnar et al, 2015).



(a) (b)

Figure 2: Feynman diagrams involving decay of positronium in (a) two photons (b) three photons



(a) (b)

Figure 3 (a) Arrangement of scintillators (bird's eye view). b) Front view with photons. We created these detectors in the GEANT4 simulator.

5.5 Data analysis:

Detect and characterise the positronium formation events using the coincidence detector system. Using the total number of ortho-positronium formed, we would be able to calculate the cross-sectional area of positronium formation. We would know the flux of positrons at the given beam energy. Moreover, we would detect the number of ortho-positronium formed. Thus, we could then mathematically calculate the differential cross section area(to be calculated because it has not yet been calculated for this interaction at such high energies) of self-decaying ortho-positronium at the given positron energy and the lifetime of o-Ps in different environments. These values have not been calculated in previous experiments for such energies and could lead to some interesting results.

6. What we hope to take away

The experience at CERN or DESY would be extremely enriching for us. It would allow us to better understand particle physics at one of the world's best centres for scientific research. Being able to conduct this experiment would not only increase our theoretical knowledge, but also allow us to appreciate the complexity involved in setting up the experimental procedure and detection mechanisms at such large scales. Particle accelerators, especially the ones at CERN and DESY are epitomes of modern physics and engineering and have awed generations of scientists. Moreover, after our experiment in CERN or DESY, we would be able to inspire many more students in our schools to take an interest in physics. In conclusion, carrying out our experiment at CERN would indeed be a gratifying experience for us.

**Word count of Main content ~1600 words*

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