Beam DreamSTEAM

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How Does The Amount of Open-Volume Defects in Concrete Affect the Lifetime of a Positron?

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April 10, 2021

1. Introduction

Defined as irregularities in the lattice structure of a solid, open-volume defects occur when a number of atoms forming the internal surfaces in the crystal are absent [7]. Defects can allow moisture to penetrate the material, posing a significant threat to the integrity and safety of infrastructure. Some examples of material defects are faulty wiring, leaks in the ceiling and instabilities in foundations. Furthermore, defects can act as a crack nucleation site which can result in a fracture. Material defects occur in multiple forms, such as vacancies, interstitials, precipitates, dislocations, disclinations, grain boundaries, twin boundaries, and even cracks, all of which can occur at different scales [7]. This causes a change in a material's electrical and optical properties, both of which are vital to designing thermomechanical treatments in the materials industry. Therefore, it is important that we investigate methods in detecting open-volume defects as these can have drastic impacts on the behaviour of materials and how others use it.

2. Experiment

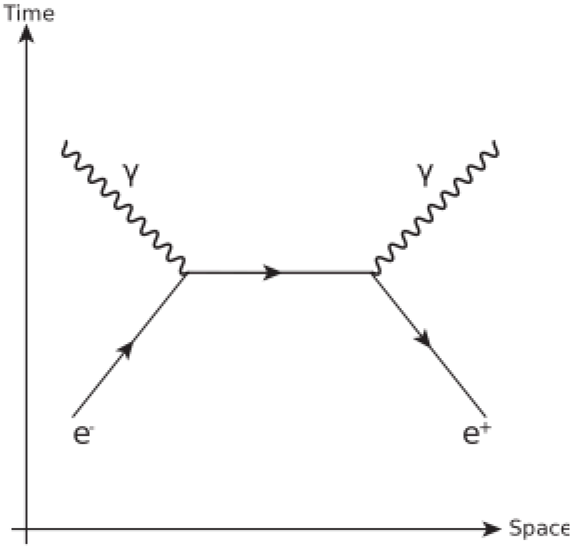
2.1 Research Question

In this experiment, we will be focusing on detecting the gamma-rays emitted by the positron electron annihilation in order to detect open-volume defects in the concrete sample. We will be analysing the use of a high-energy positron beam for positron annihilation lifetime spectroscopy (PALS). Specifically, how Does the amount of open-volume defects in concrete affect the lifetime of a positron?

2.2 Theoretical Background

Positron interactions with matter are split up into two different phases: ionisation and annihilation. A high velocity positron will interact with the atomic electrons through electrostatic forces of attraction. As it moves along, electrons are gradually pulled out of the atoms which in turn will ionize the respective atoms. A small amount of kinetic energy is lost by the positron since the pull of an electron will reduce the velocity of the positron. If the material is an insulator, the positron will come into close contact with an electron and form positronium (as it has lost most of its energy), before entering a chain of annihilation interactions. Positronium is a short-lived unstable system consisting of an electron and a positron [6].

Figure 1: Positron Annihilation displayed in a Feynman Diagram [8]



After annihilation occurs during the positron's interaction with the material, two or three photons of equal energy (0.511 MeV) and momentum in the γ-ray spectrum, are emitted. The lifespan of the positron until annihilation is determined by the density of the material. A higher density will in turn have more atoms and electrons present, which creates a greater loss in energy of the accelerating positron as it interacts with more electrons. Thus, this results in a shorter lifespan for the transitory positron. Respectively, the converse will transpire in vacancies where a longer lifespan will beget a lower density. This can be used to stipulate and forestall irregularities in materials such as concrete. Through the usage of a Scintillator-Photomultiplier detector, we can measure the positron lifetime as the output pulse produced at the scintillator is proportional to the time difference between the birth and the annihilation of the γ-quanta. [1] Since the positronium intensity is correlated to the time evolution of the total porosity [4], we can manipulate this variable by taking advantage of the fact that the porosity can be affected by the water-cement ratio. A higher water concentration will fabricate a more porous material as an increased volume will produce larger water droplet gaps. This will make the concrete more porous due to a higher frequency of air gaps which form greater vacancies, illustrating potential defects in susceptible materials.

Therefore, in line with existing literature, we hypothesize that the positron lifetime is proportional to the porosity of concrete. It can thus be used as a measure for open-volume defects.

$$\lambda = \frac{1}{\tau} = \pi {r_0}^2 c \int |\psi^+(r)|^2 n\_(r) \gamma \, dr$$

λ : Annihilation rate

τ : Positron Lifetime

$|\psi^+(r)|^2$: Positron Density

$n\_(r)$: Electron Density

r : Radius

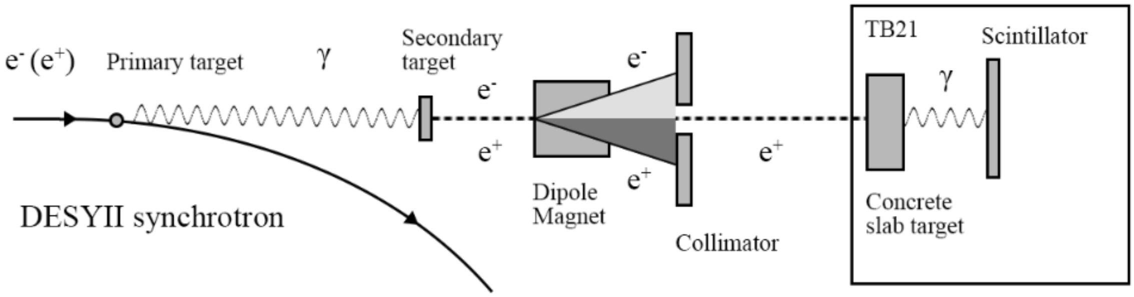
r_0 : Electron Radius

This process is used for the characterization of solid materials as positron states extracted from the timing spectrum can identify structural defects [5]; this is also known as positron annihilation lifetime spectroscopy (PALS). It is typically carried out with the use of ^{22}Na as source of β^+ radiation wherein the positron energy extends up to 540 keV [1]. Experimental data postulates [3] that applying a high-energy beam for this purpose, could yield higher data rates (due to nearly perfect efficiency in determining implantation time and better calculation of measurement volume) by controlling the energy and direction of the positrons during implantation in concrete. In this experiment, we will investigate the use of a high-energy positron beam for positron annihilation lifetime spectroscopy and determine whether this provides an optimal solution to identifying the ortho-positronium decay [5] in the pores of concrete structures.

2.3 Methodology

For our experiment, we want to accelerate a beam of positrons towards cement. Following that, we want to compare the lifetime of the positron depending on the different water-cement ratio which will affect the porosity of the cement.

Figure 2: Experimental Setup to Measure the Positron Lifetime in Various Porosities of Cement



Procedure:

1. First, prepare 5 concrete slabs of the various water-cement ratios shown in Table 1 will be prepared with the dimensions of 0.6m x 0.4m x 0.1m which is a common (3:2) ratio used in cement slabs (Fig 3).

   The water-cement ratios that are listed below are the ones that are most commonly used. It is found that the lower the ratio (less water), the higher strength of the concrete. To make the following water-cement ratios by using the formula:

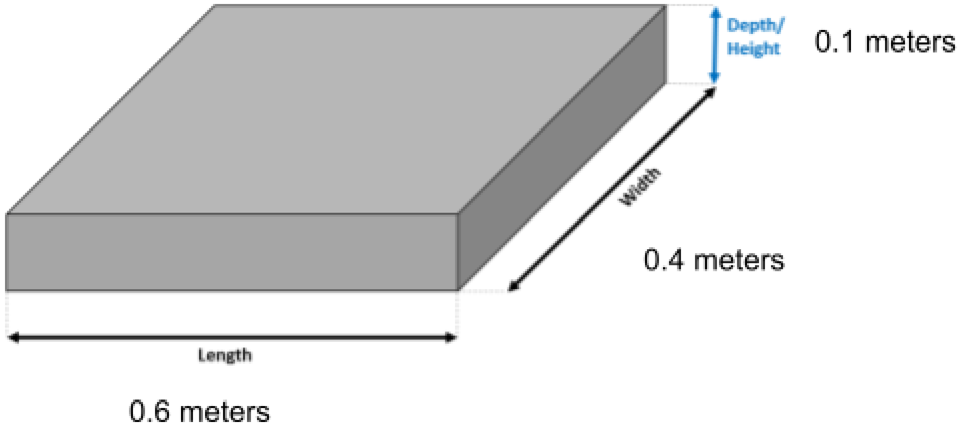
   $$Required\ volume\ of\ water\ = (Ratio\ \cdot\ Cement\ Volume)\ /1000\ .$$

   The cement volume will be constant at $0.024m^3$.

Table 1: Water-cement ratios

Setup	Strength [9]	Water-Cement ratio	Required amount of water (m^3)
1	Extreme	0.40	0.0000096
2	Very Severe	0.45	0.0000108
3	Severe	0.50	0.0000120
4	Moderate	0.55	0.0000132
5	Mild	0.60	0.0000144

Figure 3: Dimensions of the Cement Slab



2. For this experiment, DESY II Synchrotron will be used. A concrete slab will be placed in the Test Beam area 21 in front of the accelerator for the test beam to collide with it.
3. Next, a collimator will be placed between the beam source and target (cement slab) and set to the acceptance energy of the beam to 0.511 MeV - which is the maximum energy for the positrons in a positron beam.
4. A dipole magnet will also be placed between the collimator and the target and set to filter out the electrons, leaving a stream of positrons accelerating towards the target.
5. The scintillator will be placed behind the cement slab so that it will be on the receiving end of the gamma rays released from annihilation. Through this, the lifetime of the positron can be tracked as it collides with the slab and reaches the open-volume defect.
6. Afterwards, the amplitude of the electric pulse (from the gamma rays) that was detected by scintillator-photomultiplier will be used to record the lifetime of the positron.
7. The investigation will be repeated with the other slabs of different ratios and afterwards the positron lifetimes will be compared.

3. Application

We believe that through our experiment, we can understand an efficient way to detect the open volume vacancy defects in a material. The early detection of these defects would not only reduce the economic impact produced by the fault in the material, it can also enhance the product quality. This would be beneficial, as structures and foundations for homes can be improved and we can make sure that they are stable whenever they are faced with high impact.

4. Why We Want To Go & What We Hope To Take Away

We believe participating in the BL4S competition is an excellent opportunity, furnishing us with many distinctive prospects which have enabled us to further embellish our understanding of particle physics. As like-minded peers demonstrating an active academic interest, we hope to gain insight from an actualized investigation employing the particle accelerator and get the chance to learn from experts in the field, broadening our knowledge of particle physics and its applications.

5. Acknowledgements

We would like to thank our physics teachers, Mr Onur Gundogdu and Mr Lawrence Winter for encouraging us to partake in BL4S and supporting us throughout the development process.

6. References

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