Geant4 Simulation of Annihilation and excitation of Positronium

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Abstract

The purpose of this report is to document the work done during the summer of 2016 (18/6-26/8) as a part of the CERN Summer Student Programme. The work has been done at the AEGIS (Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy) collaboration under the supervision of Lillian Smestad and Michael Doser. The goal of the project was to create a Monte Carlo simulation in Geant4, of Positronium annihilation and excitation in the positron test chamber of the AEGIS experiment.

1 Introduction

The main goal of the AEGIS collaboration is to create and experimentally investigate antihydrogen. The used method to create antihydrogen is by charge exchange of a Positronium (Ps) atom and an antiproton. To do this one needs a bunch of laser excited Positronium atoms.

The purpose of the positron test chamber is to investigate the formation and properties of Ps and positrons. Positrons are shot in bunches onto a Positronium formation target made of meso-structured silica, which then converts the positrons into Positronium. Both ortho- and para-Positronium is created, but because the lifetime of p-Ps is much smaller than o-Ps, only the latter will be included.

The o-Ps is then send out in a random distribution, and most are annihilated in the target before escaping into the test chamber. The annihilation of o-Ps is just the annihilation of the positron and an electron in the matter the o-Ps is traveling through. This creates two 511 keV photons propagating in opposite directions and an electron which is left from the o-Ps atom.

If the o-Ps escapes into the test chamber, there is a certain chance that it annihilates with itself, which is what gives rise to the lifetime of 142 ns. The two photon annihilation in this process is suppressed because the total spin in o-Ps is 1, and instead the major decay is a three-photon decay.

The purpose of this project is to make a Monte Carlo simulation of the events happening inside the positron test chamber after creating o-Ps. The simulation is made in Geant4, which is a framework for Monte Carlo simulations of particles interacting with matter. Geant4 works by shooting one particle with a certain starting momentum and position into a user-defined volume. The geometry of an apparatus is made up of blocks, cylinders and spheres which then consists of a material with certain properties. The program then automatically invokes the relevant processes in each material and propagates the particle and possible daugtherparticles, through the volume. One can then define sensitive detector-volumes in which it is possible to collect data of the particles passing through.

However Ps atoms are not defined in Geant4 at the time of this report. Therefore the main part of this project is to implement Ps into the program, which also includes creating the decays and processes discussed earlier.

2 Simulation

In this section the different parts of the simulation is explained. I will start with the general structure of the program, and after that the implementation of Ps, and lastly explain features included specific to the AEGIS experiment.

General Structure

The main file of the program creates a RunManager which is then fed information of the particle used, the geometry of the apparatus and the physics processes included in the simulation. This is the main class of the program, and is responsible for determining the interaction of the particle and propagating the particle through the defined volume. A macro file is then read with different commands, which in this case determines the verbosity level of the program, generates a visual picture of the defined volume and lastly how many particles are simulated.

Usually when simulating in Geant4, the particles and physics processes used are already defined and therefore only needs to be included in the physicslist. That leaves it up to the user to define the starting properties of the particle and the apparatus geometry. However because Ps is not included, there is a little more work in the physicslist for this simulation than usual.

Positronium

In this part I will go through how the Ps atom is implemented in the simulation. First the atoms basic properties is defined in the G4ParticleDefinition class. These are things like mass, spin, lifetime and so on. The decaytable of the particle is also included here by first making a G4DecayChannel class and filling in the applicable decaychannels and their respective branching ratios. In each decaychannel the process must be defined.

For the ground state o-Ps the two-photon decay is suppressed because of spin conservation. Therefore I have only included one process which is the three-photon decay. The energy distribution of two of the photons in this decay is given by:

$$F(k_1) = 2 \cdot \frac{k_1(m-k_1)}{(2m-k_1)^2} - \frac{2m(m-k_1)^2}{(2m-k_1)^2} \ln \frac{m-k_1}{m} + \frac{2m-k_1}{k_1} + \frac{2m(m-k_1)}{k_1^2} \ln \frac{m-k_1}{m},$$

where $m = 1022\,\mathrm{keV}$ and k_1 is the energy of the photon. The last photon has 1022 keV minus the energy of the first two photons. The direction of propagation of the photons are uniformly distributed but such that they conserve momentum in each decay.

To include the possibility to laser excite the atoms, I have created different states. This is done by defining a new particle for each state needed, and then adding the relevant lifetime, decays, branching ratios and processes to each new particle. The process of exciting the atoms with a laser is not included in geant4, and therefore I have implemented that. Likewise the decay from an excited state into the groundstate, is something I have made since this is not included in geant4.

Lastly the pick off annihilation with the walls of the chamber is added. This is done as a discrete process. To do this I have copied the code for positron annihilation and changed it such that it works for Ps. The process does not take into account the electron left behind from the Ps atom, which should not make a significant difference in the result of the simulation. The cross section of this process is kept the same as for positron annihilation.

Positron Test Chamber

The positron test chamber is in this simulation made up of 5 cylinders with varying lengths and inner radii, but all has the same outer radius. This creates a closed chamber which is radially symmetric around the x-axis which is the beam axis. In one of the cylinders, there is a cylindric hole on the top and bottom for the placement of the sensitive detectors. This is done by creating 3 volumes, the big cylinder and two smaller ones, and then using boolean operations to get the final shape. All of these volumes are made of aluminum and the rest of the "world" volume is vacuum. Lastly the sensitive detectors are added. These are both cylindric and placed in the center of the hole made for them. The detectors are $PbWO_4$ scintillators. These detectors are added as sensitive volumes such that their class is called after each step done by a particle inside the detectors volume. This detector class takes care of the data acquisition by writing the desired data into a .txt file in each call. The collected data can be changed in the src/cSenDet.cc file, which is the sensitive detector class.

The starting position of the Ps atoms is not the same place for every atom. The atoms are placed such that they make a Gaussian distribution on a disk in the y-z plane with a FWHM of 4 mm. The starting momentum direction is uniformly distributed in all directions and the magnitude is determined from a Maxwell Boltzmann distribution with a temperature of 1300 K. These starting conditions are made to emulate the conditions of a Ps atom created in the positron test chamber.

3 Reflection on the programme

In this section I will give a quick comment of the activities attached to the CERN Summer Student programme.

The lecture program which lasted 6 weeks has been mostly good and very interesting to attend. A couple of different lecture programs have especially stood out to me. First the lectures given by Tara Shears on "Particle World" was very interesting. These lectures were the first proper introduction given to some of the work done at CERN, and Tara was very good as the first lecturer we had. She is very friendly which made the auditorium a very nice and relaxed place to learn. After that Andrew Cohen's lectures on "Theoretical Concepts in Particle Physics" were all excellent for me as a physicist. He is very good at including the students in his lecture and giving great perspectives to the math he did on the blackboard. Lastly I want to mention Michael Doser's lectures on "Antimatter in the lab" as the ones I enjoyed the most. The concept of antimatter is really interesting to me (I may have been influences by working in his group), and Michael did a great job at making his lectures easy to understand by most of the students.

I have enjoyed working on my project at the AEGIS collaboration a lot, and Lillian has been a very good supervisor to me. She asked me even before I came to CERN what I would like my project to be about, which has given me the opportunity to choose to try programming on a larger scale than I have done previously. I also feel like she has given me space to try things myself, and has given me a lot of control of what to do and when to do it. Whenever I asked for help, she always gave me all the time I needed and was very helpful in finding people who could help if she could not. The project has been more difficult than I imagined, but that has also made it very rewarding when I made progress.

Also throughout my stay here, she has showed me around the experiment several times, even though my project itself did not require that. Every time I have had a question about the progress of the experiment or some of the problems they have had, she has also taken the time to explain everything to me. This has all been great for me, because it has given me a greater understanding of not only experiment but also how it is to work at CERN full time.

Lastly I will just say that I have had a great time at CERN this summer, and I have become much closer with the people around me than I had anticipated. Being around the other summer students every day for 10 weeks, has made me some amazing friends, and given me a very different perspective of people from other parts of the world.