Low-Energy Photon Time Tracking GEANT4 Simulation Program for Gamma Spectroscopy Experiments Using GAGG Scintillator

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Background

- Efficiencies in Scintillators are Extremely Important As There is Only Short Amount of Time Available to Conduct Experiments Due to the Restricted Use of the Large Colliders at Facilities Such As RIBF at Riken; GAGG is an Excellent Candidate Because It Has a Very High Efficiency (Density of 6.6 g/cm3) Compared to Other Previously Used Scintillation Materials Such As the NaI:TI (Density of 3.7 g/cm3) and the CsI:TI (Density of 4.5 g/cm3) [1].
- In Gamma Spectroscopy Experiments, It is Very Important to Determine the Configuration of the Scintillator That Will Produce the Best Energy and Time Resolutions.
- There Currently Does Not Exist a Simulation Program That Shows the Time Resolution of the Gamma Spectroscopy Experiments With GAGG Scintillator of Different Properties.
- To Determine the Time Resolution of the Gamma Spectroscopy Experiments, the Most Important Process is Having the Data of the Time Differences Between the Fundamental Gamma Ray Emissions and the Low-Energy Photons That are Detected at the Photocathode.
- This Document Aims to Explain the Algorithm and the Results of the Newly Developed GEANT4 Simulation Program That’s Biggest Goal is to Record the Time Differences Between the Fundamental Gamma Photon Releases and the Photocathode Detected Low-Energy Photons for Different GAGG Scintillator Properties, Which Will Be Crucial Sets of Data in Determining the Time Resolution of Each of the Considered Scintillator Properties and for Eventually Identifying the GAGG Scintillator Configuration That Yield the Best Time Resolution.

Algorithm - Vector

- Vector Was Chosen to Store Information Regarding Time for All of the Particles in the Experiment.
- The Reason for Using a Vector Instead of Other Popular Data Structures Like the Stack or Trees is Because the Complexity for Random Access and Insertion of the Elements, Which is Used Very Frequently in the Implemented Algorithm (Further Explained in the Upcoming Slides), are O(1) for Vector Compared to O(N) for Stack and Typically O(log(N)) for Trees [2][3].
- As Seen in FIG 1, Each Element of the Vector Represents a Unique Particle. Each Element of the Vector Stores the Time Difference Between the TrackID Particle's Current Position in the Scintillator and the Emission of Its Parent Fundamental Gamma Photon.

1 ns	5 ns	15 ns	10 ns	20 ns
Index: 0 TrackID: 1	Index: 1 TrackID: 2	Index: 2 TrackID: 3	Index: 3 TrackID: 4	Index: 4 TrackID: 5

FIG 1. Illustration of the Vector, With a Simple Example Assuming Only 5 Particles Were Produced in the Simulation. As Shown, Each Element With Index i-1 Stores the Time Difference Between the TrackID = i Particle's Current Location in the Scintillator and the Emission of Its Parent Fundamental Gamma Photon.

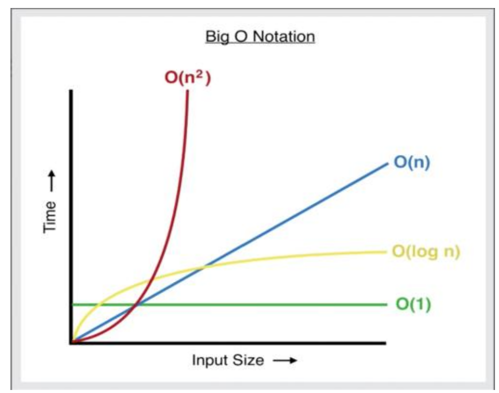


FIG 2. Graph Showing the Performances of Each Algorithm Complexity [4]. The Constant Algorithm Complexity is Much More Efficient Than Others Especially for a Very Large Input (Vector) Size, Which is What's Expected As All of the Produced Particles are Being Tracked.

Algorithm - Vector

Initial Conditions of the Vector:

- Values of All the Elements are Equal to 0.
- Size of the Vector is Set to a Constant Size.
- The Size is Approximated By the Total Number of Particles in the Experiment.

This Can Be Estimated By Running a Test Simulation and Checking the Number of Created Low-Energy Photons Since Most of the Particles From the Experiment are Low-Energy Photons.

Note That the Number of Created Low-Energy Photons is Linearly Proportional to the Number of Gamma Photons As Most of the Low-Energy Photons are Made From the Gamma Photons.

0 ns	0 ns	0 ns	0 ns	0 ns
Index: 0 TrackID: 1	Index: 1 TrackID: 2	Index: 2 TrackID: 3	Index: 3 TrackID: 4	Index: 4 TrackID: 5

FIG 3. Illustration of the Vector, With a Simple Example Assuming 3 Low-Energy Photons Were Created in the Test Simulation Run. Given This Information, the Size of the Vector is Set to Be Slightly Greater Than the Number of Created Low-Energy Photons, in This Case 5, to Also Account for the Gamma Photons and Possibly the Electrons. As Also Shown in the Illustration, All of the Element Values are Initially Set to 0.

Algorithm – 1st Condition

- If the Particle Type of the Step is a Fundamental Gamma Photon and Its Element Value is 0, Then Enter the 1st If Statement.

```
if((fdata->arr[(theTrack->GetTrackID())-1])==0.0 && (theTrack->GetParentID())==0)
```

FIG 4. Screenshot of the 1st Condition of the Algorithm

- Above Information Shows That It is the 1st Time This Fundamental Gamma Photon is Being Detected.
  Therefore, the Time Difference Between Its Emission and Its Current Position in the Scintillator is Just Equal to the Step Time.

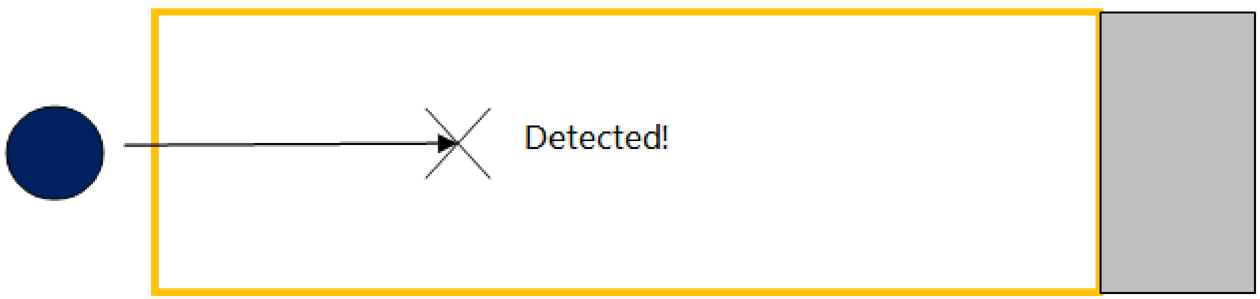


FIG 5. Illustration of Example 1 of the Experiment, Blue Circle Being Gamma Source, Yellow Box Being GAGG Scintillator, Grey Box Being Photocathode, Black Line Being Gamma Photon Emission, and X Being the Point of 1st Detection. As Shown, the Time Difference Between the 1st Point of Detection and Its Emission From the Gamma Source is Simply Equivalent to the Step Time.

```
(fdata->arr[(theTrack->GetTrackID())-1])=(theStep->GetDeltaTime());
```

FIG 6. Functionality of the 1st Condition of the Algorithm. Setting the Step Time As the Element Value of the Detected Fundamental Gamma Photon.

Algorithm – 2nd Condition

- If the Particle Type of the Step is NOT a Fundamental Gamma Photon and Its Element Value is 0, Then Enter the 2nd If Statement.

```
else if((fdata->arr[(theTrack->GetTrackID())-1])==0.0 && (theTrack->GetParentID())!=0)
```

FIG 7. Screenshot of the 2nd Condition of the Algorithm

- Above Information Shows That It is the 1st Time This Electron or Low-Energy Photon is Being Detected.
- Given the Defined PhysicsList for the Simulation Program, Electrons are Produced By Gamma Photon Via Compton Scatter and Photoelectric Effect, and Low-Energy Photons are Produced By Both Gamma Photon and Electron Via Compton Scatter and Electron Scatter/BremStrahlung. Thus, the Detected Electrons and Low-Energy Photons Must Have a Parent.

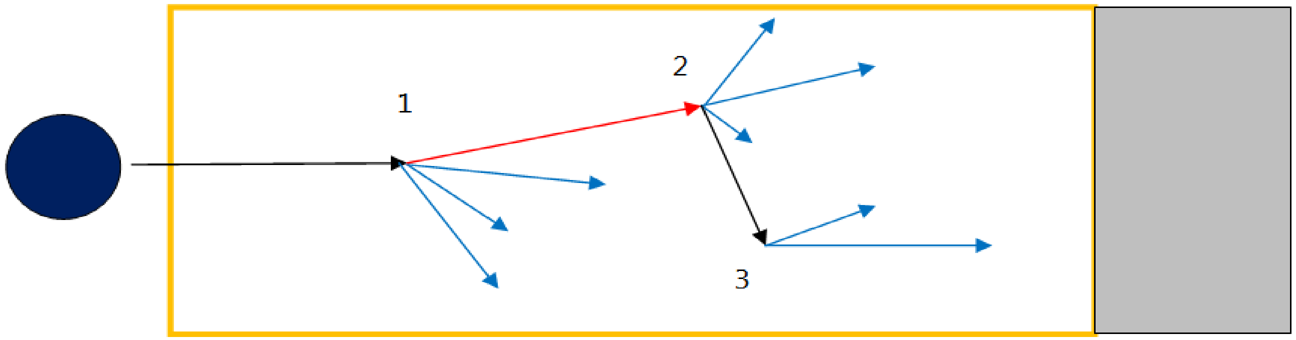


FIG 8. Illustration of Example 2 of the Experiment, Red Line Being Electron Emission, and Blue Lines Being Low-Energy Photon Emissions. 1) Shows Fundamental Gamma Photon Producing Electron and Low-Energy Photons, 2) Shows Electron Producing Non-Fundamental Gamma Photon (via Electron Scatter/BremStrahlung) and Low-Energy Photons, and 3) Shows Non-Fundamental Gamma Photon Producing Low-Energy Photons.

Algorithm – 2nd Condition

- Since the Element Value Should Store the Time Difference Between the Detected Particle's Current Location in the Scintillator and the Emission of Its Parent Fundamental Gamma Photon, Not Only Should the Life Time of the Detected Electron/Low-Energy Photon Be Considered (In This Case, Life Time = Step Time), But Also the Time Difference Between the Last Location of the Parent Particle Before the Production of the Detected Particle and the Emission of Its Parent Fundamental Gamma Photon.

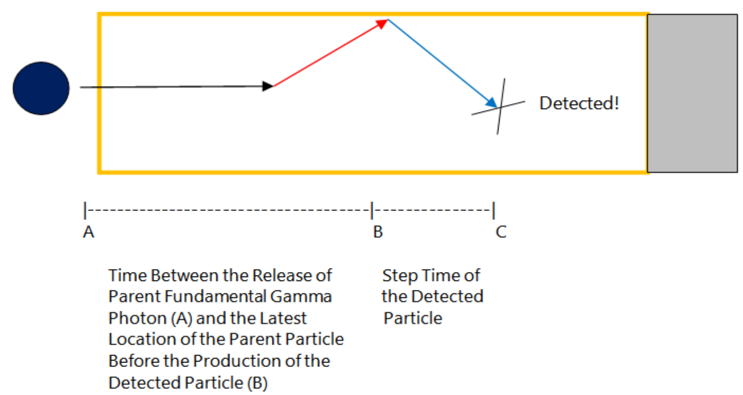


FIG 9. Illustration of Example 3 of the Experiment, X Being the Point of Detection. As Shown, to Determine the Time Difference Between the Parent Fundamental Gamma Photon Emission (A) and the Point of 1st Detection of the Low-Energy Photon (C), Not Only Should the Step Time of the Low-Energy Photon (Time Difference Between B and C) Be Taken to Account, But Also the Time Difference Between the Parent Fundamental Gamma Photon Emission and the Parent Particle's Last Position Prior to Producing the Low-Energy Photon (Time Difference Between A and B).

- Therefore, Set the Element Value to Step Time + Element Value of Its ParentID Particle, Which Stores the Time Difference Between the Latest Location of the Parent Particle Before the Production of the Detected Particle and the Release of Its Parent Fundamental Gamma Photon.

```
T1 = (fdata->arr[(theTrack->GetParentID())-1]);
T2 = T1+(theStep->GetDeltaTime());
(fdata->arr[(theTrack->GetTrackID())-1]) = T2;
```

FIG 10. Functionality of the 2nd Condition of the Algorithm. T1 is Equal to the Element Value of the ParentID Particle (eg. Time Difference Between A and B in FIG 9), and T2 is Equal to the Step Time of the Detected Particle (eg. Time Difference Between B and C in FIG 9). The Sum of T1 and T2 is Set As the Element Value of the Detected Particle (eg. Time Difference Between A and C in FIG 9).

Algorithm – 3rd Condition

- If the Particle of the Step Has an Element Value Not Equal to 0, Then Enter the Else Statement.
- Above Information Shows That This Particle Has Already Been Detected Before. To Update the Element Value to the Time Difference Between Its New Location in the Scintillator and the Emission of Its Parent Fundamental Gamma Photon, Just Add the Step Time to the Current Element Value.

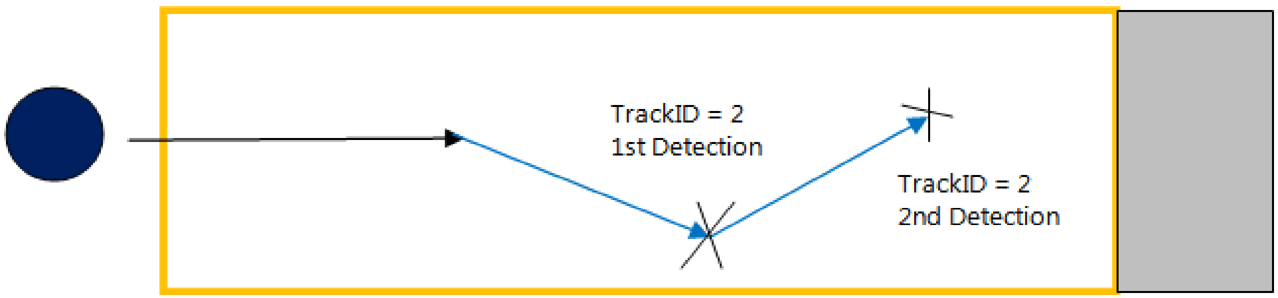


FIG 11. Illustration of Example 4 of the Experiment, X Being the Points of Detection of the Low-Energy Photon. Because the Vector Element for TrackID = 2 Particle Currently Stores the Time Difference Between Its 1st Detection in the Scintillator and Its Parent Fundamental Gamma Photon Emission, the Step Time Should Be Simply Added to the Existing Element Value to Update the Value to the Time Difference Between Its 2nd Detection in the Scintillator and Its Parent Fundamental Gamma Photon Emission.

```
(fdata->arr[(theTrack->GetTrackID())-1]) += (theStep->GetDeltaTime());
```

FIG 12. Functionality of the 3rd Condition of the Algorithm. The Step Time is Being Added to the Existing Element Value of the Detected Particle.

Algorithm - Detection

- At the End of Each Condition, It is Checked If:
  1) the Detected Particle is a Low-Energy Photon
  2) the Detection is Made at the Photocathode
  If Both of These Conditions are Satisfied, Then the Element Value of the Corresponding Low-Energy Photon is Added to a Different Vector That's Purpose is to Store Only the Time Differences Between Low-Energy Photons' Photocathode Detections and Their Corresponding Parent Fundamental Gamma Photon Emissions.

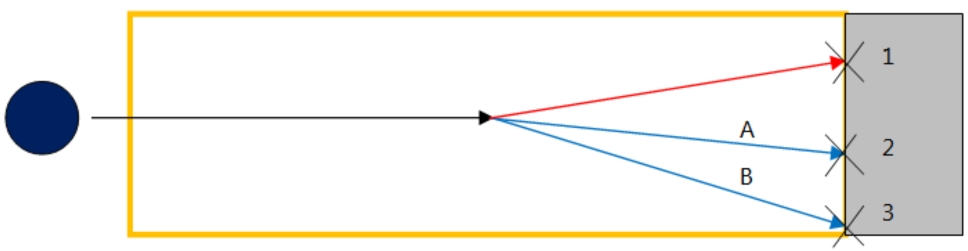


FIG 13. Illustration of Example 5 of the Experiment, X Being the Points of Photocathode Detection of the Electron and the Low-Energy Photons.

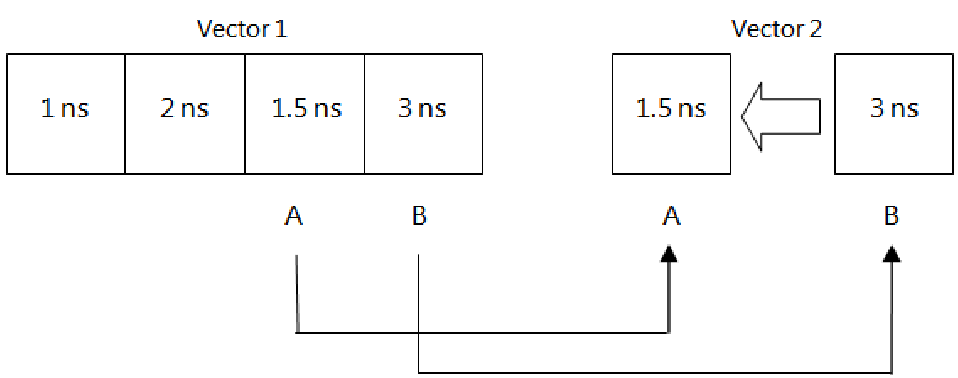


FIG 14. Vector 1 Stores the Time Differences Between Each Particle's Most Recent Location and the Emission of Its Parent Fundamental Gamma Photon, Whereas Vector 2 Stores the Time Differences Between ONLY the Photocathode Detected Low-Energy Photons and Their Parent Fundamental Gamma Photon Emissions. As Shown (Using the Example From FIG 13), Only the Vector 1 Element Values Regarding the Photocathode Detected Low-Energy Photons (A and B) are Added to Vector 2.

Limitation

- There is One Limitation to the Implemented Algorithm; Let's Look at the Example Diagram Below to Demonstrate:

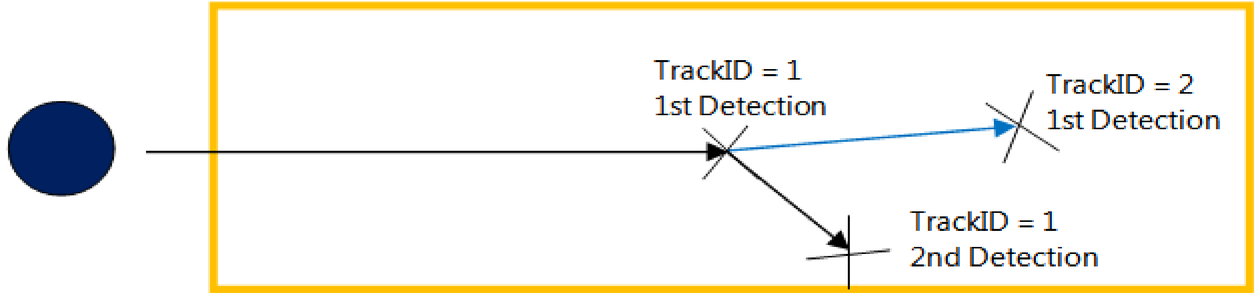


FIG 15. Illustration of Example 6 of the Experiment

As Explained Earlier, the Element Value of TrackID = 2 Particle Should Store the Time Difference Between the Emission and the 1st Detection of TrackID = 1 Fundamental Gamma Photon + the Time Difference Between the 1st Detection of the Fundamental Gamma Photon and the Detection of the Low-Energy Photon.
However, If the 2nd Detection of the Fundamental Gamma Photon is Made Before the Detection of the Low-Energy Photon, Then the Element Value of the Low-Energy Photon Will Include the Time Difference Between the Emission and the 2nd Detection of the Fundamental Gamma Photon Instead of the Correct Value Which is the Time Difference Between the Emission and the 1st Detection of the Fundamental Gamma Photon.
This Problem However is Negligible Because the Number of Detections Per Fundamental Gamma Photon is Very Low, eg. ~ 5 Per Fundamental Gamma Photon With Very High Initial Energy of 2000 KeV, and Every Step Time of the Fundamental Gamma Photon With Very High Initial Energy of 2000 KeV is Very Small, eg. < 10 ps.

Result

- Configuration of the GAGG Scintillator for These Example Simulations is 25 X 25 X 100 [mm]

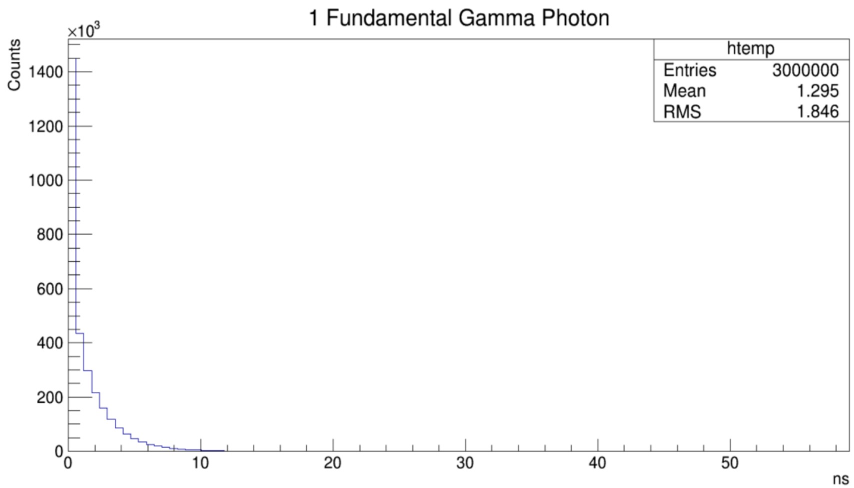


FIG 16. Plot: Time Differences Between Particles' Latest Locations and Their Parent Fundamental Gamma Photon Emissions (All)

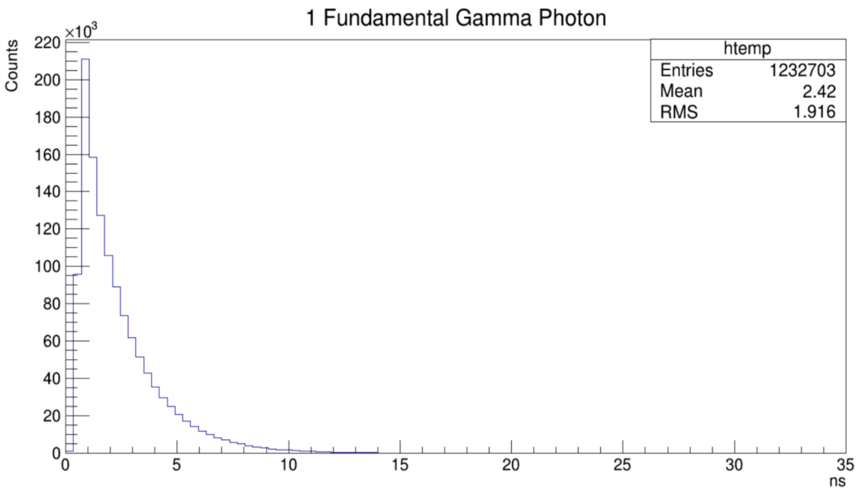


FIG 17. Plot: Time Differences Between Photocathode Detected Low-Energy Photons and Their Parent Fundamental Gamma Photon Emissions (All)

For the 1st Example Simulation Run, 1 Fundamental Gamma Photon Was Emitted Per Event and the Energy Per Fundamental Gamma Photon Was 2000 KeV.

FIG 16 Shows the Plot of the Vectors That Store the Time Differences Between Each Particle's Most Recently Detected Location and the Emission of Their Parent Fundamental Gamma Photon, of 100 Events.

The Vector Size For Each Event Was Chosen to Be 30000 Because the Number of Created Photons Per Event Was Mostly Approximately 27000.

A Large Number of Counts at 0 ns However Implies That the Vector Size Was Approximated Much Larger Than the Actual Number of Created Particles Per Event, As This Shows That Many of the Elements Which All Represent Unique Particles Remained Unchanged Since the Initialization of the Vectors.

FIG 17 Shows the Plot of the Vectors That Store the Time Differences Between the Photocathode Detected Low-Energy Photons and the Emissions of Their Parent Fundamental Gamma Photon, of 100 Events. The Average Time Outputted to Be 2.420 ns and RMS to Be 1.916.

Result

If More Data is Needed to Make Even More Accurate Approximation of the Time Difference Between the Photocathode Detected Low-Energy Photons and Their Parent Fundamental Gamma Photon Emissions, One Way is to Increase the Number of Fundamental Gamma Photons (or the Number of Events).
FIG 18 Shows the Plot of the Same Example From the Previous Slide Except This Time With 3 Fundamental Gamma Photons Instead of 1.This Simulation Provided More Precise Approximations, the Average Time Being 2.422 ns and RMS Being 1.919.
The User of the Simulation Program Also Has an Option to Look at the Results of an Individual Event, As For Example FIG 19 Shows the Results From Event 45.

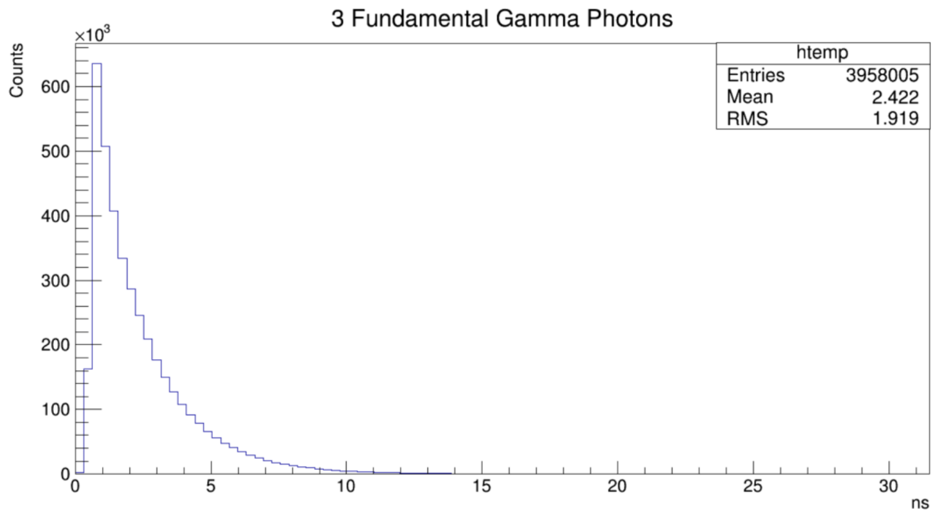


FIG 18. Plot: Time Differences Between Photocathode Detected Low-Energy Photons and Their Parent Fundamental Gamma Photon Emissions (All)

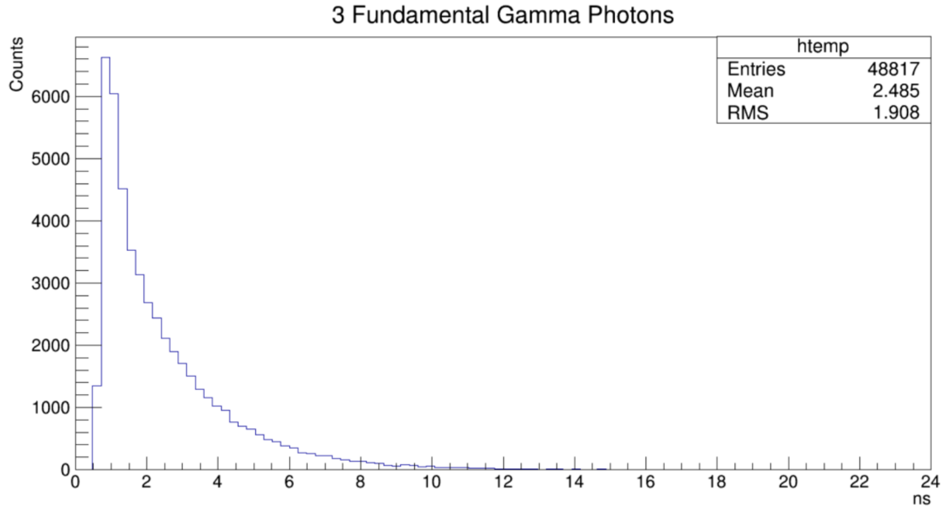


FIG 19. Plot: Time Differences Between Photocathode Detected Low-Energy Photons and Their Parent Fundamental Gamma Photon Emissions (Event 45)

Result

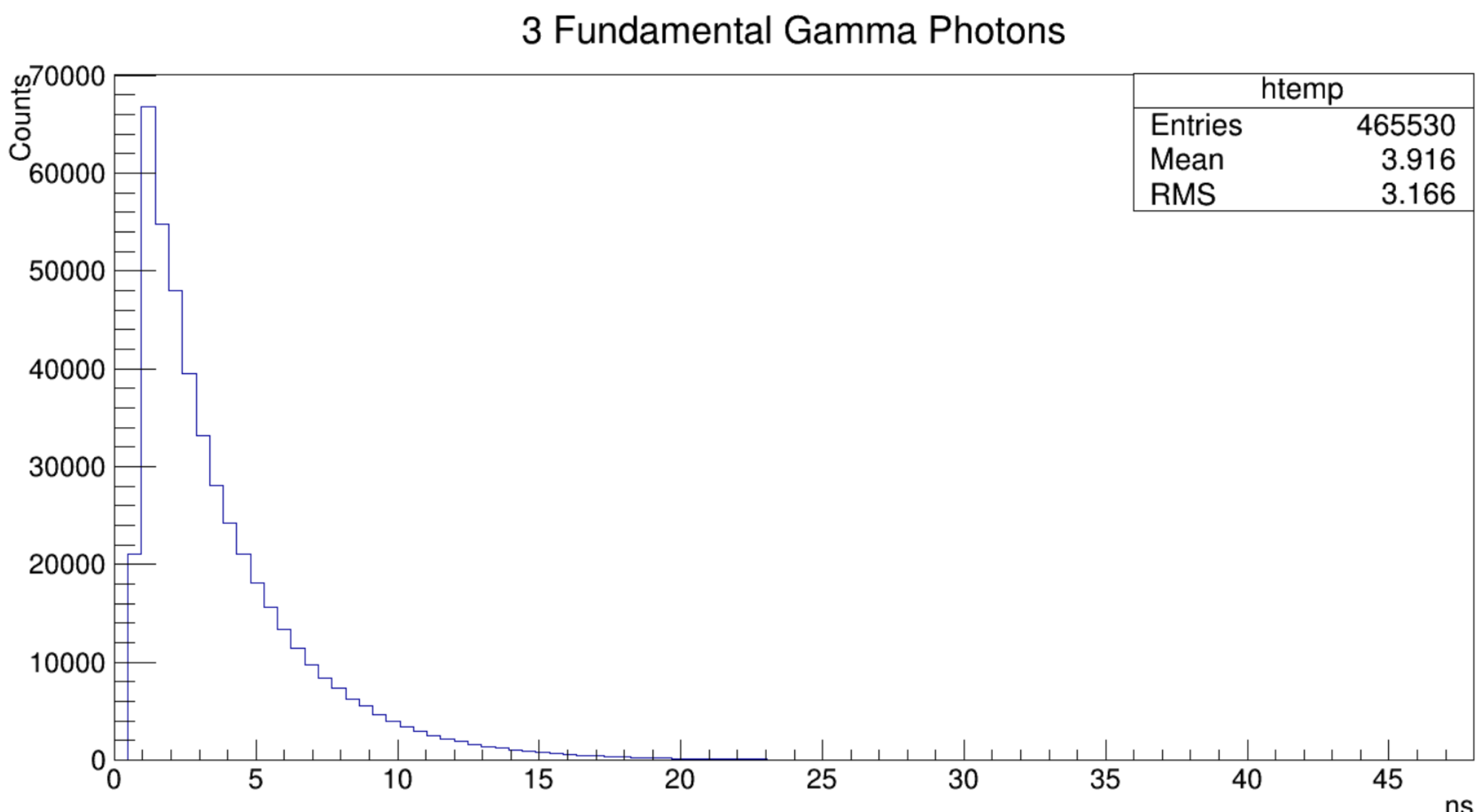


FIG 20. Plot: Time Differences Between Photocathode Detected Low-Energy Photons and Their Parent Fundamental Gamma Photon Emissions (All)

- Configuration of the GAGG Scintillator for This Example Simulation is 50 X 50 X 200 [mm], Which is a Larger Volume Than the Past Examples. Other Experiment Conditions Were Mostly Same As the Example From the Previous Slide, ie. 3 Fundamental Gamma Photons Were Released and the Energy Per Fundamental Gamma Photon Was 2000 KeV, Except This Time, 50 Events Were Simulate Instead of 100. As Expected, Like Shown in FIG 20, the Average Time Difference Between the Photocathode Detected Low-Energy Photons and Their Parent Fundamental Gamma Photon Emissions (3.916 ns) Was Greater Than When the Scintillator Configuration Was Smaller (2.422 ns).

Appendix

Basic Instructions to Set the Experiment Conditions and Run the Simulation

-To Set the Number of Fundamental Gamma Photons, Go to geant/GAGG/src and PrimaryGeneratorAction.cc, and Modify the Variable Called n_particle on Line 25.

-To Set the Energy Per Fundamental Gamma Photon, Go to geant/work and set.dat, and Modify the Variable Called Gamma.Energy on Line 4.

-To Set the Configuration of the GAGG Scintillator, Go to geant/work and set.dat, and Modify the Variables Called Scint.Height, Scint.Width, Scint.Depth on Lines 20, 21 and 22.

-To Set the Vector (Called arr) Size, Go to geant/GAGG/src and DataManager.cc, and Modify the Lines 67 and 69.

-To Modify the Algorithm of the Time Tracking Simulation Program, Go to geant/GAGG/src and SteppingAction.cc.

-To Compile the Simulation Program, Go to geant/GAGG and Type ‘make’ on the Command.

-To Run the Simulation Program, Go to geant/work and Type ‘GAGGSim -n (NUMBER OF EVENTS) –o (OUTPUT FILE) –s set.dat’ on the Command.

-To See the Results From the Simulation, First Open the Output File in ROOT By Typing ‘root OUTPUTFILE.root’ on the Command.

To Check the Time Differences Between Each Particle’s Last Detected Location and the Emissions of Their Fundamental Gamma Photon

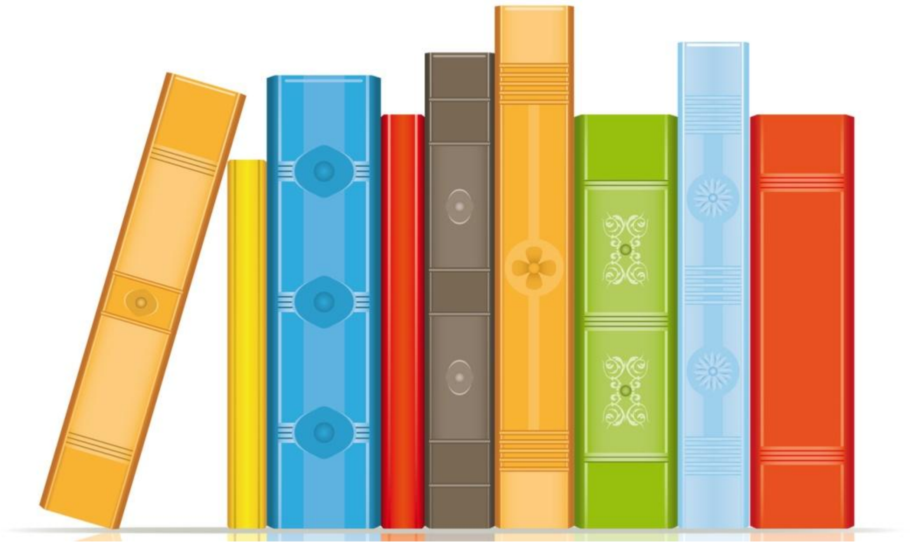
1) of All Events: Type ‘str->Draw(“TimeofParticles”)’ on the Command.
2) of Event X: Type ‘str->Draw(“TimeofParticles”,””,””,1,X)’ on the Command.

To Check the Time Differences Between Photocathode Detected Photons and the Emissions of Their Fundamental Gamma Photon

1) of All Events: Type ‘str->Draw(“TimeofDetectedParticles”)’ on the Command.
2) of Event X: Type ‘str->Draw(“TimeofDetectedParticles”,””,””,1,X)’ on the Command.

Reference

[1] Pawel Sibczynski, Andrzej Broslawski, Aneta Gojska, Vasili Kiptily, Stefan Korolczuk, Roch Kwiatkowski, Slawomir Mianowski, Marek Moszynski, Jacek Rzadkiewicz, Luksaz Swiderski, Adam Szydlowski, Izabella Zychor, NUKLEONIKA 2017; 62(3): 223-228
[2] en.cppreference.com/w/cpp/container/vector
[3] www.bigocheatsheet.com
[4] kuanhsuh.github.io/Javascript-Algorithm.html



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