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Angular Distribution of Delta Electrons in SAGE Spectrometer using Geant4

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Abstract

This simulation work is intended to describe the angular distribution of (δ) electrons in a spectrometer that is designed for simultaneously measuring gamma-rays and electrons called SAGE Spectrometer using the Geant4 simulation toolkit. The angular distributions were identified for various target materials including lead, gadolinium, tin, aluminium and carbon. In heavy ion atom collision, the direct ionization of the target elements and the scattering of electron due to the Two-Centre Coulomb forces are the dominant contributions. The direction of (δ)electrons produced in a heavy ion collision hitting a heavy element target is strongly focused in the forward and backward directions with a large suppression at perpendicular angles. For light element targets the (δ) electrons are almost entirely forward focused. This indicates that the distributions are (Z) dependent. The main features of the (δ) electrons coming from SAGE spectrometer are characterized by looking at their angular distributions produced from a reaction between a Ca^{48} ion beam and a lead target.

Introduction

In the study of heavy elements via gamma spectroscopy it is important to measure both conversion electrons and gamma rays simultaneously. Therefore, designing a spectrometer with the ability of measuring both plays a vital role and may provide detailed information about the structure of the heavy element. The SAGE spectrometer has been implemented in the Accelerator Laboratory at the University of Jyv$\ddot{a}$skyl$\ddot{a}$ in conjunction with the JUROGAM II array of germanium detectors [1]. In the reaction of an ion beam with a heavy target material, low energy electrons are released in the forward direction, known as delta (δ) electrons. These low energy electrons are also detected by the silicon detectors in the SAGE spectrometer as a source of unwanted background in the conversion electron spectra unless a special suppression is used. The relationship between the energy of the electrons, $E(\delta)$, the energy of projectile, (E_p), the K-electron binding energy of the target atom, (E_K), and electron-to-ion projectile mass ration $(\frac{m_e}{m_p})$ is given by [2]:

$$E(\delta) = 4\left(\sqrt{\frac{m_e}{m_p}E_k E_p} + \frac{m_e}{m_p}E_p\right) \qquad (1)$$

A cloud of non-zero rest mass electrons surrounds the small, dense and positively charged nuclei of the atom of both the ion and target material. In a heavy ion collision these electrons are emitted in any direction with a variety of energies from near zero to the tens of keV. In this work more attention has been paid to distinguish the main features of the angular distributions of the (δ) electrons in such reactions, which are mainly dominated by ionization process of the target atom. Electrons of the target atoms may undergo several physical processes including multi scattering, ionization and bremsstrahlung [3]. Therefore, we rely on Geant4 simulations to provide a better understanding of the delta electron distributions. The process of emitting delta electrons occurs in heavy ion-atom collision. When a fast heavy-ion impinges on the target it interacts via the Coulomb forces which causes the target atoms to become excited and ionized. The (δ)

electron emission depends on the proton number and the impact parameter, or closeness of approach, of the target. The object of this project is focused on the analysis of the angular distribution of the emitted delta electrons which were simulated in Geant4 by reactions between Ca^{48} at 200 Mev and targets with varying (Z). Geant4 was used to construct a ring of Silicon detectors around the reaction position to obtain the angular distributions [4, 5]. A fixed target thickness was used for heavy and light targets to investigate the effects of (Z). The effect of increasing the energy of the Ca ion beam was also investigated. This work aims to exhibit the main features of the delta electron angular distributions observed in SAGE in order to be able to suppress the maximum number of delta electrons from reaching the silicon detector in the SAGE spectrometer. However, the delta electrons were sufficiently abundant to contaminate the conversion electron spectrum detected by the 90 segmented rings and strips of SAGE. In turn, this makes it difficult to identify the prompt, or true, electron-gamma coincidences, allowing us to re-establish the placing of a high voltage barrier (-50 kV) in front of the silicon detector [1].

Projectile- Target Interaction Collision Process

Ionization mechanisms in two- and three-particle processes can be investigated through describing the physical parameters which illustrate the Coulomb force interactions, which include the projectile-electron impact parameter, b_e, the projectile-target impact parameter, b_N, and the distance vector between electron-target nucleus, $(\vec{r}_e)$. Fig 1 shows a pictorial representation of a collision process [6].

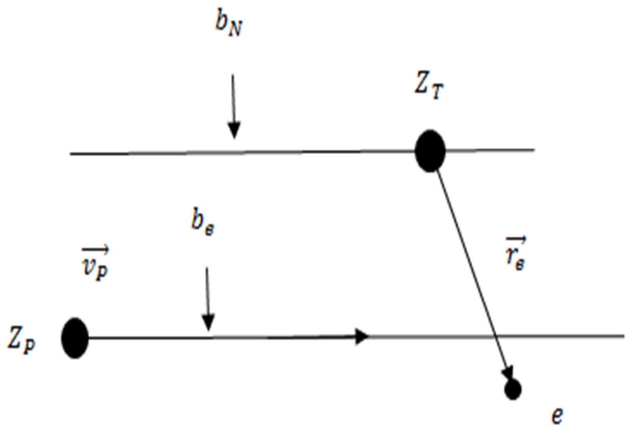

Fig 1: Schematic diagram of a heavy ion and target collision process.

In such an ionization reaction, we have a heavy charged ion beam colliding with one of the target's electrons. As a result there will be a Coulomb interaction which can be expressed based on the impact parameters [7]. Firstly, when the impact parameter b_e is very small compared to the b_N, i.e. $b_e \ll b_N$, there will be a production of the delta electrons, which is called binary encounter electron emission. This is due to the two body collision process occurring between the projectile ion and the target electron resulting in the ionization of the target atom. The energy of the binary electrons, $E_e(BE)$, can be calculated from energy and momentum conservation given by [8]:

$$E_e(BE) = 2m_eV_p^2\cos^2\theta \qquad (2)$$

where m_e , V_p^2 and θ are the mass of the electron, velocity of the projectile and the angle of emission respectively. From the above formula we see that, for a fixed projectile energy, the electron energy depends only on the emission angle. The maximum energy occurs when the electron is emitted parallel or antiparallel (θ = 0, 180) to the beam. When this knock-on collision happens, the above equation becomes:

$$E_e(BE) = 2m_eV_p^2 \qquad (3)$$

The other case occurs when the impact parameter b_e is approximately the same or a slightly greater than b_N. In this case there will be ionization due to a three-body interaction called the Two Centered Electron Emission (TCEE) process. Initially, the incoming ion projectile knocks out the electron of the target atom, then the emitted electrons experiences a scattering by the target nucleus itself. In this case, the delta electron will be emitted and created from a soft collision process, where there is a small momentum transfer between the projectile nucleus and the target electron. In TCEE the angular distribution of the electron is isotropic with respect to the Lab frame [9]. While the delta electrons are emitted strongly in the forward direction due to the polarization effects of the electronic states and the Coulombs force for the massive projectile. At low energy, in heavy ion collision several other types of emission processes are occur, for instance Auger electron emission from both projectile and target and projectile-electron loss. The contribution from those emission processes are relatively small and beyond the purpose of the current work [6].

Geant4 Simulation Toolkit

Geant4 is a simulation package constructed for the simulation of particles over a wide range of energy passing through and interacting with matter [10]. Geant4 is developed and maintained by the European Organization for Nuclear Research (CERN). Geant4 is well validated and has made significant contribution to many nuclear physics experiments preformed worldwide. In this present work Geant4 simulation are utilized to analyse the angular distribution of delta electron produced in SAGE Spectrometer experiments.

Simulation Procedures

A. Detector Construction class

As it is represented in Fig. 2, in order to construct the geometry set up (World volume, Target and Pixels) were defined as a box with given dimensions. A thin target box was also defined with a thickness of $20\mu\text{m}$. Different target materials of lead, gadolinium, tin, aluminium and carbon were used for the simulation. In total 24 Si pixel detectors of 12 cm in size were positioned 85 cm from the target to form a ring surrounding the target. To avoid over detecting the ion beam intensity, Si pixel 1 was divided into two smaller detectors to create a slight gap to allow the scattered ions to escape without being detected.

B. Primary Generator Action class

The calcium ion beam was generated with energy of 200MeV, with a charge state $q = +10$, originating 85 cm from the target. The beam ions are slightly deflected by Coulomb repulsion with the target nuclei before exiting the array, as seen by the yellow line(s) in Fig. 2.

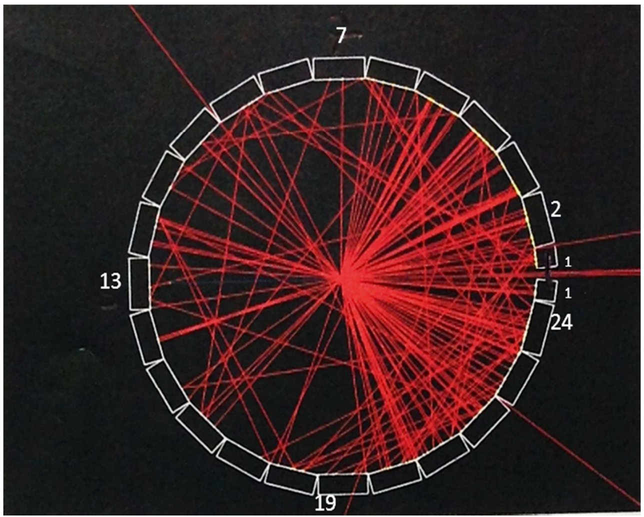

Fig 2: Geant4 Visualization of 100 collision events between 200 MeV Ca^{48} projectiles Lead (Pb) target. A circle of 24 silicon pixel detectors surround the target. The target is placed at the center of the array. The Ca^{48} ion projectile located at some nominal distance from the left side of the target position and close to pixel 13. The red lines indicate the delta electrons.

The sorted data was used to produce a schematic diagram of angular distributions. The experimental set up visualization is shown in Fig. 2. To represent any interesting physics in this report the code was run for 10^5 events. The effect of varying beam energy and the target materials on the angular distribution was investigated. For that reason, two kinds of targets, lead and carbon, were chosen and the code was run for

200MeV and 800MeV projectiles. The target thickness was fixed to 1000 atom layers thick, representing approximately 10µm.

Results And Discussion

A. *Angular Distribution for Different Target Materials*

A simulation of 10^5 projectile events were analysed for each setting. The data is plotted as a function of Si pixel detector, which can be translated to angle since each pixel represents a 15-degree coverage. Figs. 3-5 show the result of a 200 MeV Ca^{48} beam impinging on the different target materials. Comparing the angular distributions in Figs. 3-5, it can be concluded that the cross section for δ electron production is highest for lead and lowest for carbon at all angles, showing a relation to the proton number of the targets, Z = 82 and 6 respectively. It can be concluded that the production of δ electrons is (Z) dependent. In addition, the area under the backward peak diminishes as the (Z) of the target decreases. This is attributed to the fact that the center of mass for light targets will have a greater velocity when given momentum in a collision with a heavy Calcium beam ion. In the case of a heavy target, due to the strong two-center Coulomb forces of the projectile and the target nuclei, the emitted electrons may undergo an effective bouncing off. The angular distribution is mostly forward focused for lighter targets and more symmetric in forward and backward angles for heavier targets.

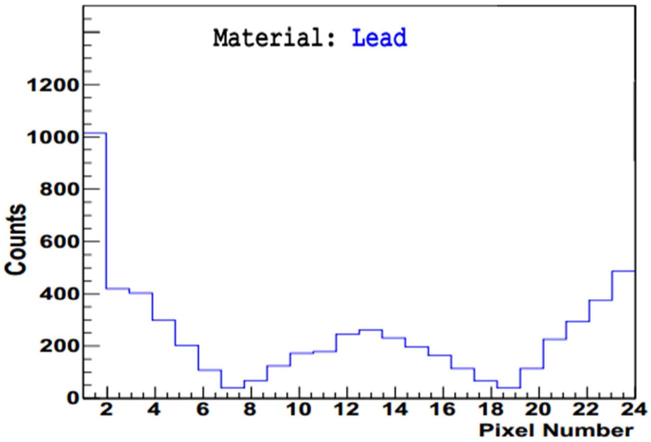

Fig 3: Angular distribution of delta electrons from 10^5 simulated events in Geant4 using a lead (Z = 82) target. The pixel numbers represent the location of each detector at 15 degree angle intervals.

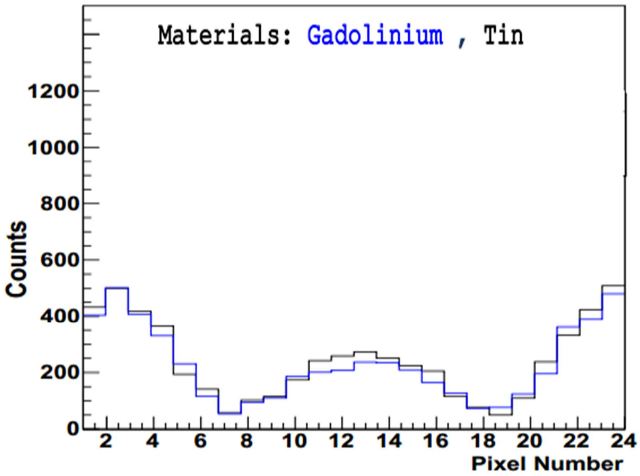

Fig 4: Angular distribution of delta electrons from 10^5 simulated events in Geant4 using a gadolinium (Z = 64, blue) and tin (Z = 50, black) target. The pixel numbers represent the location of each detector at 15 degree angle intervals.

All results show the same general behavior, the largest δ electron production occurs in the forward direction with significant suppression perpendicular to the incident projectile direction.

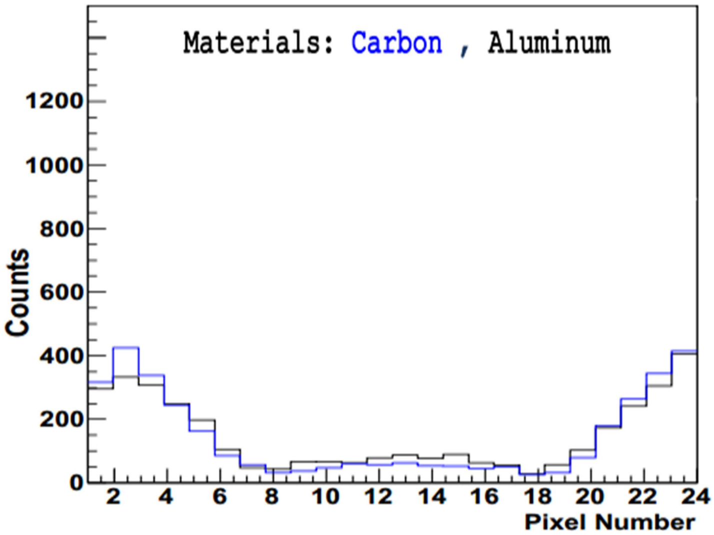

Fig 5: Angular distribution of delta electrons from 10^5 simulated events in Geant4 using a carbon (Z = 6, blue) and aluminium (Z = 13) target. The pixel numbers represent the location of each detector at 15 degree angle intervals.

B. *The Effect of varying Ion Projectile Energy*

The effect of increasing the ion projectile energy was also investigated and the results are shown in Figures 6 and 7. Beam energies of 200 and 800 MeV were investigated for the heaviest, lead, and lightest, carbon, targets. For the Pb target, as the energy of the ion is raised an unexpected reduction by about two orders of magnitude in counts in the forward direction can be observed in the angular distribution from Geant4. For the C target a similar effect is observed where a factor of 2 fewer δ electrons were detected in the forward direction as beam energy was increased from 200 to 800 MeV. This result, may indicate that the electrons are scattered more randomly and hit the first pixel less, assuming that Geant4 is the most robust tool. Thus, further investigation is needed.

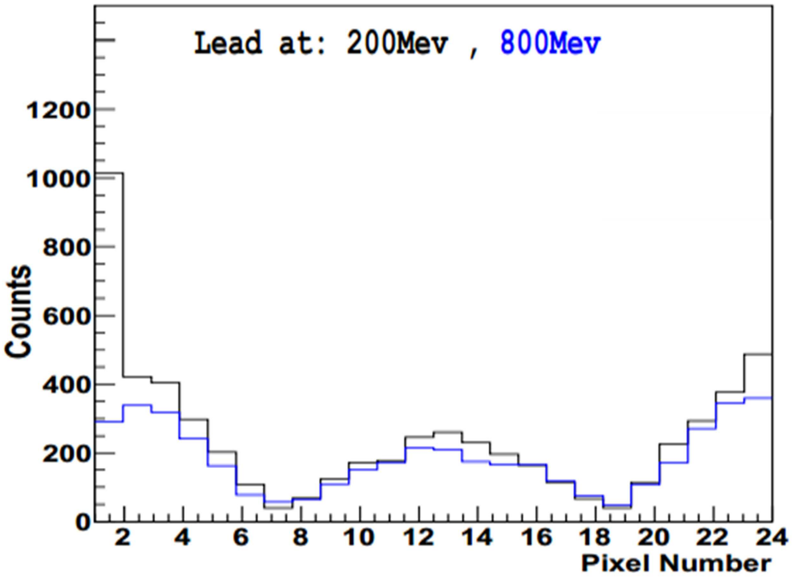

Fig 6: A comparison of the angular distributions of delta electrons obtained for a 10^5 events from a Geant4 simulation with projectile energies of 200 MeV (black) with 800 MeV (blue) for a lead (Z = 82) target.

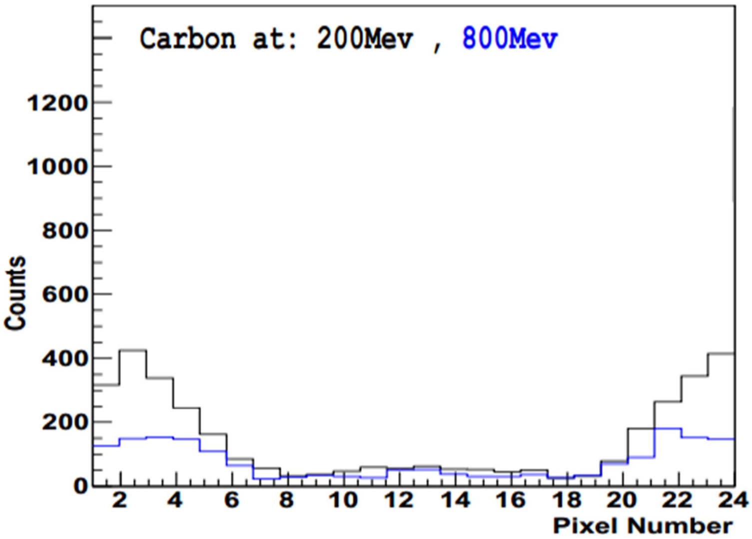

Fig 7: A comparison of the angular distributions of delta electrons obtained for a 10^5 events from a Geant4 simulation with projectile energies of 200 MeV (black) with 800 MeV (blue) for a carbon (Z = 6) target.

Conclusion

Overall, it is emphasized that Geant4 Monte Carlo simulation can provide a convenient result and a well-defined shape for angular distributions of reactions between ion beams with a variety target materials. This is one part of a full Geant4 simulation that was performed while designing the SAGE spectrometer. Delta electrons produced in heavy target are strongly forward focused. The backward peak is relatively large in heavy target elements, while highly-suppressed in lighter target materials. A relation can be determined between the production of delta electrons and their angular distribution with the proton number of the target. It can be understood as the centre of mass of the system for the light elements moves forwards, but for heavy elements due to strong Coulomb forces the probability of back scattering electrons becomes larger. However, the details of these processes have not been fully investigated. An unexpected reduction in the cross section and the angular distributions were observed as the energy of the ion beam increased. Thus further work is required to test these simulation results against delta electron distribution from experimental data to obtain a clear understanding of the discrepancies, as well as to refinement the simulations. Finally, based on this work it is recommended to place the SAGE array detector in the backward direction. Additionally, the suppression of these delta electron can be achieved using a high voltage barrier between the SAGE silicon detector and the target chamber. For more detail on the SAGE refer to [3]. A detailed simulation needs to be performed using the whole SAGE spectrometer.

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