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A Geant4 simulation package for the SAGE spectrometer

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Abstract. A comprehensive Geant4 simulation was built for the SAGE spectrometer. The simulation package includes the silicon and germanium detectors, the mechanical structure and the electromagnetic fields present in SAGE. This simulation can be used for making predictions through simulating experiments and for comparing simulated and experimental data to better understand the underlying physics.

1. Introduction

The SAGE spectrometer [1, 2, 3] is a combined conversion electron and γ-ray in-beam spectrometer. It is combined with the RITU gas-filled recoil separator [4] and the GREAT focal-plane spectrometer [5] for recoil-decay studies. For the detection of γ rays SAGE employs the JUROGAM II germanium-detector array [6] which consists of 24 four-fold segmented clover, and 10 EUROGAM Phase I type germanium detectors all using Compton-suppression shields. For the detection of conversion electrons a highly segmented silicon detector, consisting of 90 pixels, is used together with a solenoidal magnetic transport system. SAGE uses three solenoid coils for the production of the magnetic field, two upstream of the target and one downstream. The downstream coil lies on the beam line while the two upstream coils are on a different axis. This solenoid axis is in near collinear geometry with the beam line in order to minimise Doppler broadening. The beam passes close to the silicon detector as the two axes form an angle of $3.2°$.

Magnetic shielding is used in order to suppress the stray magnetic field in the vicinity of the photomultiplier tubes of the Compton suppression shields of JUROGAM II. An electric field gradient, induced by a high-voltage (HV) barrier, was introduced in the region between the target and the silicon detector aiming to reduce the low-energy background due to the detection of δ electrons produced in heavy ion atomic collisions. A carbon foil unit (CF unit) positioned between the target and the HV barrier separates the helium-filled target chamber from the high-vacuum volume in the rest of the spectrometer and beam line. SAGE uses a fully digital data acquisition system which can handle count rates up to $30\,\text{kHz}$ per detector compared to $10\,\text{kHz}$

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per detector that the conventional analogue system could handle. This helps to open the way to the in-beam study of nuclei produced with cross-sections as low as 10 nb.

Simulations for the performance of SAGE were carried out during the design stage using the simulation code SOLENOID [7] and are presented elsewhere [1, 2]. These simulations concentrated solely on the electron part of the spectrometer and were limited to two-dimensional cylindrical geometries with the addition that the beam could be emitted on a direction other than the symmetry axis. SAGE cannot be accurately represented in cylindrical geometry since part of the setup lies on a different axis. In order to overcome this restriction, a Geant4 [8] simulation package has been developed. Geant4 enables construction of the geometry in three-dimensional space, thus the angle between the solenoid and beam axes, as well as any other non symmetrical components of SAGE can be integrated in the simulation. Additionally with Geant4 the JUROGAM II germanium-detector array can be combined with the electron detection system. Geant4 allows a more realistic representation of the spectrometer and provides detailed information on the electron motion within SAGE. This includes the volumes where electrons are lost through interactions with the surrounding material and the restricting factors in the transmission of electrons at different energies.

The advantage of the Geant4 simulation is not only that it can be used to test the performance of SAGE, but also when used prior to an experiment to assist in the tuning of the electromagnetic fields to optimise electron transmission and for making estimates of detection power for known or predicted transitions. It can be used to compare experimental results (i.e. number of measured electrons and gamma rays, fraction of detected conversion electrons from different atomic shells etc.) with simulated results to better understand the underlying physics. Using the Geant4 simulation the Doppler shift on different energy electrons can be simulated and used in the analysis of experimental data. The production and transmission of δ electrons from the target to the detector can also be studied using the Geant4 simulation toolkit and can be simulated for different beam-target configurations.

2. The geometry of SAGE within Geant4
An extensive part of the geometry of SAGE was built in Geant4 including the volumes in which the electrons and γ rays could interact. The simulated components are shown in Figure 1. For visualisation purposes the electron part of SAGE is transparent in the figure and only half of JUROGAM II is presented. The HV barrier is visible through the beam pipe and the silicon detector, CF unit and target position are also indicated. The BGO shield housing modules of JUROGAM II are visible along with the heavy-metal collimators close to the target (in red). The detector end caps of the Phase I detectors are shown in white. On the top left part of Figure 1 a detail of the target region shows the target position, the CF unit and the different vacuum volumes.

The electric and magnetic fields used in the simulation were produced using the *Vector Fields OPERA 3D* simulation package [9]. The magnetic field simulation includes the solenoid coils and the magnetic materials in close proximity (mainly the magnetic shielding). For the electric field the HV barrier and all the metal surfaces in its vicinity are included in the simulation. The calculated values were extracted from *OPERA 3D* on a three-dimensional grid and introduced into the Geant4 simulation.

3. Results and outcome of simulations
Geant4 was mainly used to study the effect that different parts of SAGE have on the electron transmission and detection efficiency. This results can be compared with previous simulations (published in [1] and [2]) and with the measured efficiencies obtained using different experimental settings. An example of simulated efficiencies is presented in Figure 2 which employed an electromagnetic field produced with 1000 A current through the coils and -30 kV on the HV
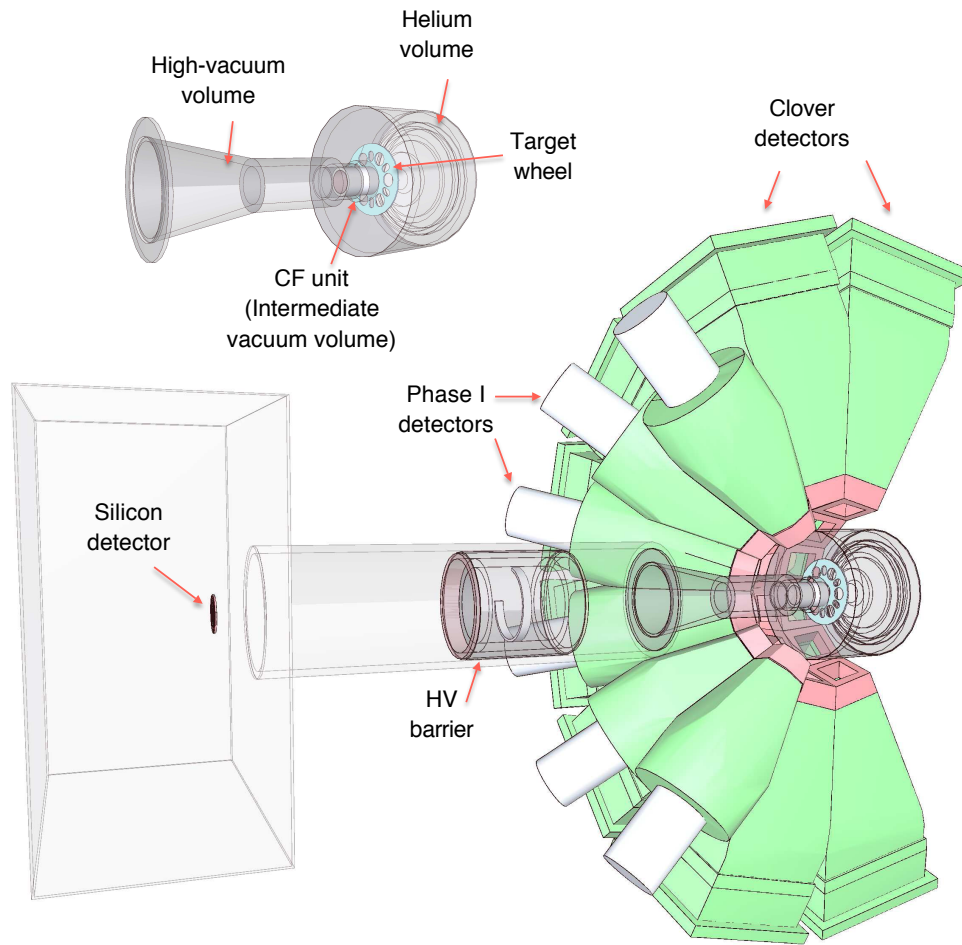
Figure 1. Schematic representation of the simulated volume. One half of JUROGAM II is drawn for graphical reasons. The main parts of the geometry are indicated on the figure. A detail of the target region is shown on the top left part of the figure.

barrier. The first Geant4 efficiency curve was produced with helium gas at 1 mbar pressure in the target chamber, the second Geant4 plot and the SOLENOID curve were produced without helium gas.

The results obtained by the two codes are in agreement for lower energies but have started to deviate by 100 keV. The Geant4 code shows higher efficiencies compared to SOLENOID between 100 keV and 300 keV, whereas the SOLENOID code predicts higher efficiency above 300 keV in comparison to Geant4. The discrepancies between the two codes is still not fully understood. These results are preliminary and a comparison with the measured efficiency curve needs to be made.

At lower electron energies the decrease in efficiency is mainly due to interactions with the electromagnetic fields, the helium gas and the carbon foils. The Geant4 curves suggest that the effect of the helium gas is negligible but further investigation is still necessary. At higher energies most losses arise from collisions of electrons with the CF unit structure which has the smallest radius aperture between the target and the detector. A 1 mm thick silicon detector is used in SAGE leading to a reduction of efficiency at higher energies and is responsible along with the radius of the CF unit for the drop in efficiency above 400 keV.
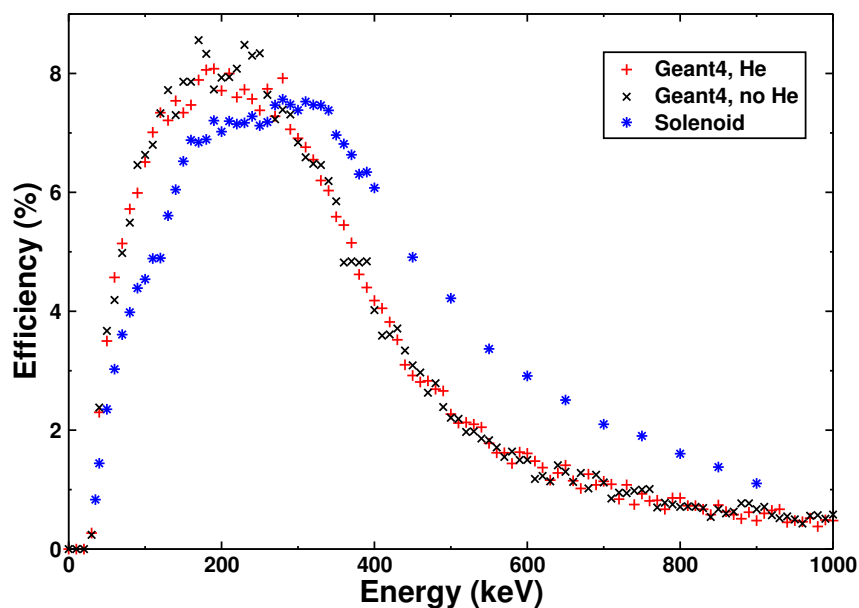
Figure 2. Simulated transmission and detection efficiencies obtained with Geant4 with and without helium at the target chamber compared with an efficiency plot obtained with SOLENOID without using helium. The simulations were produced with 1000 A current through the coils and -30 kV on the HV barrier.

The effect of the HV barrier on the electron transmission efficiency for different applied voltages was also investigated in Geant4 and is presented in Figure 3. Monoenergetic electrons between 0 and 1 MeV, in 10 keV steps, were emitted isotropically from the target position. The barrier mainly affects the lower energy electrons preventing them from reaching the detector. For example at -50 kV on the barrier almost 100% of 50 keV electrons are stopped. The effect on 100 keV electrons is less, with 70% of the electrons reflected and at 200 keV only 35% are stopped. The influence of the barrier reduces at lower voltages as can be seen in the figure.

The validity of the Geant4 simulations is tested by comparison with real data. As an example, ^{133}Ba spectra obtained through simulation and measurement are presented in Figure 4. The spectra were taken from a single, representative detector pixel indicated in the same figure. This measurement was performed in vacuum with the ^{133}Ba source placed at the target position. The current on the solenoid coils was 750 A and the HV barrier and CF unit were not used. The intrinsic resolution of the detector in the simulation was considered to be 4 keV. The two spectra were normalised with respect to the area of the 320 keV peak. The overall agreement between the spectra is very good with the only difference being a higher background on the measured one. The background is mainly caused by thermal and shot noise in the electronics which was not taken into account in the simulation.

Geant4 was also used for visualising the simulated results. An example of this is shown in Figure 5, where a source emitting electrons and γ rays at 100 keV is placed at the target position. The events shown include electrons (red lines), some of which are detected by the silicon detector, reflected by the HV barrier, interact with the surrounding material or are trapped in the electromagnetic pocket. The blue lines show γ rays, some of which interact with the germanium detectors.
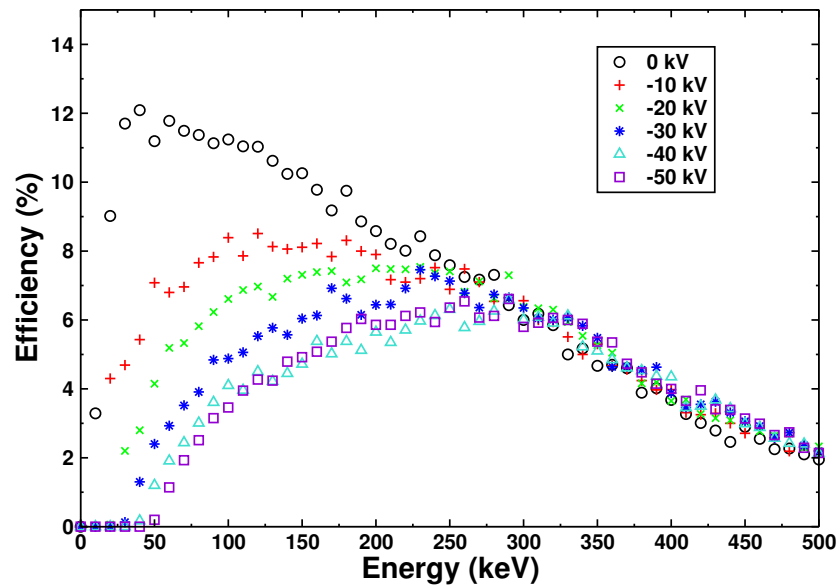
Figure 3. Effect of HV barrier on electron transmission for different barrier voltages. At higher energies the curves are identical. The amount of lower energy electrons that reach the detector reduces with increasing barrier voltage. The simulations were performed with 1000 A current through the coils and no helium present in the target chamber.
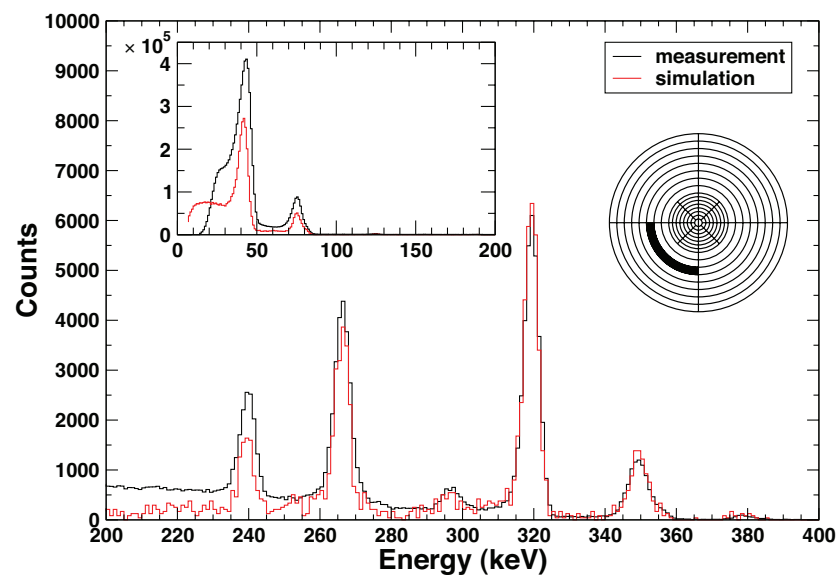

Figure 4. Comparison between measured (black) and simulated (red) ^{133}Ba spectra from the same detector pixel, shown in the detector diagram on the right. The inset shows the lower energy peaks.

4. Conclusions - Further work

The Geant4 simulation toolkit was used to produce a simulation package for the SAGE spectrometer. This package includes the SAGE silicon detector, the beam pipe, the detector and target chambers and the JUROGAM II germanium detector array (including the germanium
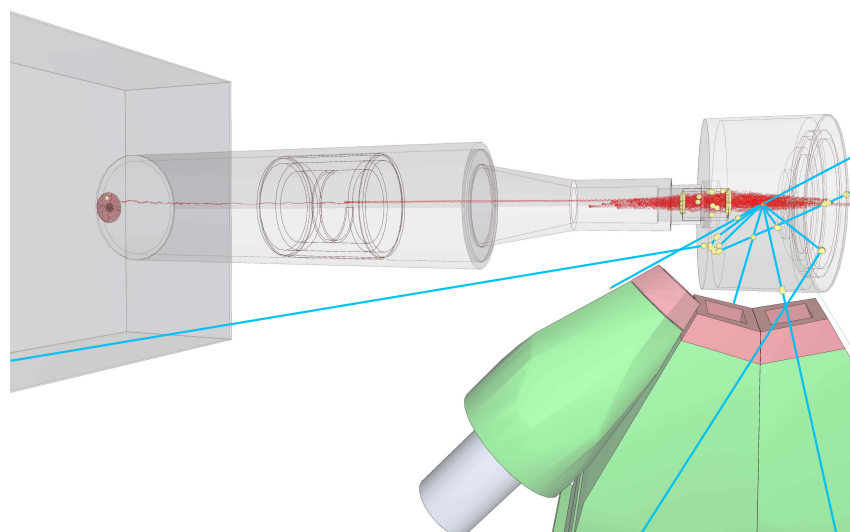
Figure 5. Example of simulated events visualised in Geant4. Electrons are presented with red lines and γ rays with blue. Some of the electrons reach the detector while the rest either interact with the surrounding material or are reflected by the HV barrier.

detectors and BGO shields with their housing and the heavy-metal collimators). The electromagnetic fields used in SAGE are imported into the code from a matrix produced separately using the *Vector Fields OPERA 3D* simulation software.

The simulation package can be used for making predictions through simulating experiments and for comparison of simulated and experimental data. It may also be used as a visualisation tool. The simulation results are within uncertainty in agreement with previously performed simulations and preliminary measurements. Further checks on the validity of the simulations are required. These include measurements of the transmission efficiency and the effect of the HV barrier.

Acknowledgments

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