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Support of Low Energy X-ray Polarization with EGS4

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Abstract

In X-ray astronomy, it is very important to detect polarization of X rays from stellar objects. There is, however, no effective polarimeter with high sensitivity for polarization. So we have been developing some types of X-ray polarimeters. For the design, computer simulation program is necessary, which is capable of simulating interaction between polarized low energy X rays and material. From the thirst, we have improved EGS4 (Electron Gamma-ray Simulation Version.4)[1][2][3] program capable of simulating the interaction with the polarized X rays lower than few hundred keV. Using the EGS4 program, we investigated the manner of polarized X rays for gas detector. As the results of the simulation with the program, we recognized that the shape of electron cloud depends on the polarization direction of the incident X ray.

1 Introduction

X-ray astronomy has progressed through the observation of stellar objects by the energy spectrum, time variability, and the image. Detectors capable of obtaining the three information have been continuously developed. On the other hand, the observation for the polarization has been rarely carried out or the development of polarimeter has not been much advanced in spite of the importance. So we have been developing some types of polarimeters sensitive to the energy range from 10 keV to a few hundred KeV[4][5][6]. The performance of polarimeters is expressed by the parameter of Minimum Detectable Polarization (MDP) as shown in the below equation.

$$MDP = \frac{429}{S\eta AF}\sqrt{\frac{S\eta A + B}{T}} \tag{1}$$

MDP	:	Minimum Detectable Polarization [%]
B	:	Background Count
S	:	Signal Counting Rate [$cm^{-2}sec^{-1}$]
η	:	Detection Efficiency
A	:	Geometrical Area [cm^2]
F	:	Modulation Factor
T	:	Observation Time [sec]

In the equation, the modulation factor represents the ability for the determination of the polarization of the incident X rays. Though it can be recognized from this equation that it is important to improve the modulation factor and the detection efficiency simultaneously, it is in general very difficult. So the optimization of the performance by computer simulation is necessary for the design of the polarimeter. As the three interactions of photoabsorption, Rayleigh scattering, and Compton scattering are dominant for low energy X rays, we have developed EGS4 (Electron Gamma-ray Simulation version.4) program capable of simulating the three interactions for the polarized X rays lower than few hundred keV. In this paper, we will describe the detail of the developed EGS4 program and the application of the EGS4 program for a gas detector.

2 Improvement for EGS4

2.1 Support of polarization

Applying new formulae for photoabsorption, Rayleigh scattering, and Compton scattering to support polarized X rays, we have developed EGS4 program.

2.1.1 Compton scattering

We used the following equation for Compton scattering cross section.

$$\frac{d\sigma}{d\Omega} \propto [\frac{k}{k_0} + \frac{k_0}{k} - 2sin^2\theta cos^2\phi], \tag{2}$$

where k_0, k, θ, and ϕ are incident X-ray energy, scattered X-ray energy, zenith angle, and azimuthal angle, respectively. As the k and θ are calculated by the original EGS4 code of subroutine `COMPT`, the azimuthal angle ϕ is determined according to the above equation by Monte Carlo method. Moreover the polarization vector of scattering X ray is determined according to the following equation by Monte Carlo method.

$$\frac{d\sigma}{d\Omega_{||}} \propto \frac{k_c}{k_0} + \frac{k_0}{k_c} - 2 + 4(1 - sin^2\theta cos^2\phi) \tag{3}$$

$$\frac{d\sigma}{d\Omega_{\perp}} \propto \frac{k_c}{k_0} + \frac{k_0}{k_c} - 2 \tag{4}$$

The polarization vector of scattered X ray has **"parallel"** vector or **"vertical"** vector. The vertical vector is perpendicular to the polarization vector of incident X ray and the direction of the scattered X ray. The parallel vector is perpendicular to the vertical vector and the direction of the scattered X ray. The direction of the two vectors is shown in Fig.1. As the polarization vector for the scattered X

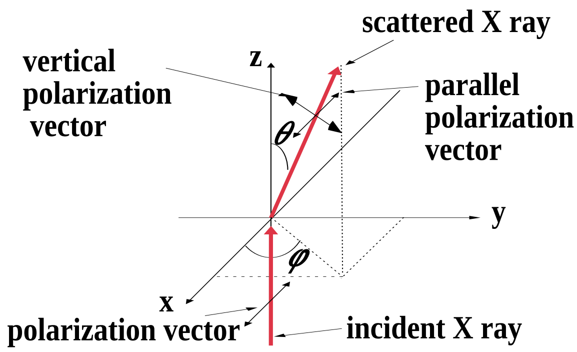

Figure 1: The two polarization vector of scattered X rays.

ray is determined in the above method, multiple Compton scattering for polarized X rays is supported in the developed EGS4 program.

2.1.2 Rayleigh scattering

We used following equation for Rayleigh Scattering cross section. As the zenith angle is determined by subroutine `PHOTON` in the original EGS4 code, the azimuthal angle ϕ is determined by Monte Carlo method according to this equation.

$$\frac{d\sigma}{d\Omega} \propto 1 - 2sin^2\theta cos^2\phi$$

As shown in Fig.2, the polarization vector of the scattered X ray has only **"parallel"** vector.

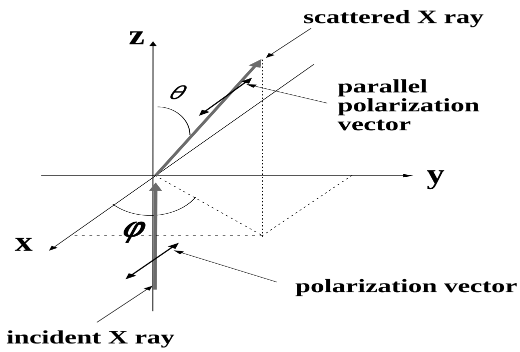

Figure 2: The manner of Rayleigh scattering.

2.1.3 Photoabsorption

We used the following equation for the cross section of photoabsorption.

$$\frac{d\sigma}{d\Omega} \propto \beta^2 sin^2\theta \frac{(1-\beta^2)^{0.5} cos^2\phi}{(1-\beta cos\phi)^4} - \frac{(1-(1-\beta^2)^{0.5}) cos^2\phi}{2(1-\beta^2)^{0.5}(1-\beta cos\theta)^3} + \frac{(1-(1-\beta^2)^{0.5})^2}{4(1-\beta^2)(1-\beta cos\theta^3},$$

where β is the speed of the photoelectron divided by light speed. Both the zenith angle θ and β are determined by in subroutine PHOTO of the original EGS4 code. According to this equation, the azimuthal angle ϕ is determined by Monte Carlo method. After photoabsorption with K-shell electron occurs, characteristic X ray or Auger electron is emitted. The probability is determined with fluorescence yield. According to the following semi-empirical equation the fluorescence yield was determined by Monte Carlo method.

$$\left(\frac{\omega_k}{1-\omega_k}\right)^{\frac{1}{4}} = 0.015 + 0.0327Z - 0.64 \times 10^{-6} Z^3,$$

where ω_k and Z are the fluorescence yield and atomic number of material, respectively. The emitted direction for Auger electron and fluorescence photon was assumed to be isotropical. The polarization vector of the fluorescence photon is determined at random.

2.2 Algorithm of the developed EGS4 program

The developed EGS4 programming codes written with Fortran consist of the EGS4 codes in which polarization is supported, user codes, interface subroutines, CERN Library developed in CERN, and CLICOM Library developed in Univ. of Tokyo[10]. They are as follows.

- **original EGS4 codes**
  `ANNIH, BHABHA , COMPT , EDGSET , ELECTR , HATCH , MOLLER , MSCAT,PAIR, PHOTO , PHOTON , SHOWER , and UPHI`
- **User code**
  `egs4main` (This is the main program) , `usr_ana , ure_ausgab , and usr_howfar`
- **interface subroutines**
  `usr_where, usr_dnear, usr_step, usr_geomread, usr_hatchsetup, usr_prehatch, usr_iausfl, usr_incident, and hbook_read`
- **Libraries**
  `CERN Library and CLICOM Library`

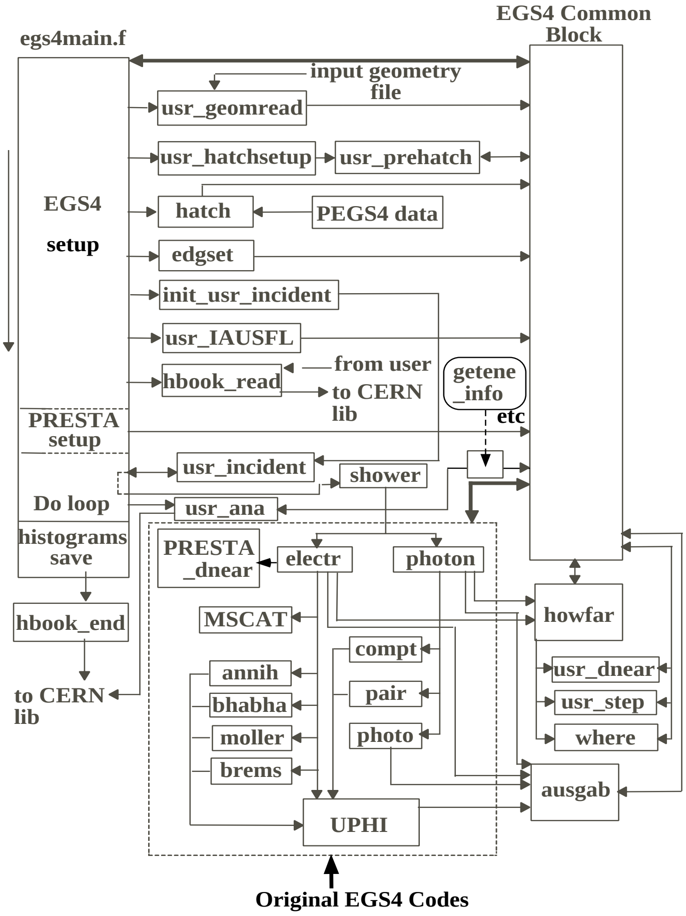

Figure 3: Algorithm for the developed EGS4 program.

The developed EGS4 program runs according to the Algorithm chart shown in Fig.3. This EGS4 program is controlled by the main program `egs4main`. Through the main program, the following initialization is carried out.

1. The dimension of simulated detector is handed to EGS4 Common Block through `usr_geomread` of interface subroutine.

2. The used material in detector is handed to EGS4 Common Block through `usr_hatchsetup` and `usr_prehatch` of interface subroutines.

3. The information of the direction, the position, and the energy for incident X rays is handed to EGS4 Common Block through `ini_usr_incident` of interface subroutine.

4. The histograms of energy spectrum for each parts of the detector are defined through `hbook_read` of interface subroutine.

5. The setup of PRESTA is carried out to simulate tracks for low energy electron in accuracy.

After them, actual simulations are carried out through `usr_incident` of interface subroutine and `shower` of the original EGS4 code. The `usr_ana` of user program makes histograms of energy spectrum for each part of detector, using the information of the deposited energy calculated in EGS4 code. The energy spectrum for each parts are saved in the end of simulation.

2.3 How to run the program

Before running the program, you must prepare for two files called geometry file and histogram file. Fig.4 (a) and (b) are examples of the geometry file and the geometry. Each row corresponds

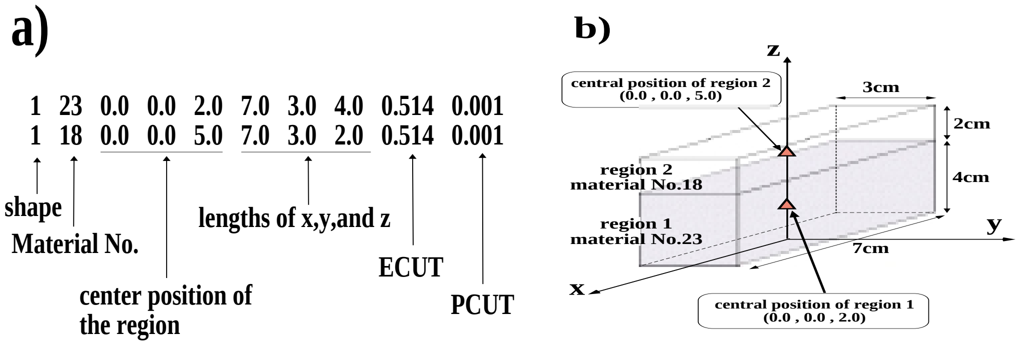

Figure 4: Fig(a) shows an example of geometry file. Fig(b) shows geometry that is represented by the example of geometry file.

to the dimension for one part of the detector. The number in the first column shows the shape of the part. For instance, the number of 1 corresponds to a rectangular parallelepiped. The shapes of sphere and column are also supported with the number of 2 and 3. The number in the second column corresponds to kind of material. For example, the number of 23 is a plastic scintillator. The numbers from the third column to the fifth column correspond to the center position of the part. In the case that the shape is rectangular parallelepiped, the numbers from the sixth number to the eighth number correspond to the lengths of three sides. The ninth number and the tenth number correspond to cut of energies for electron and photon, respectively. The following is an example of histogram file. With this file, the histogram for each part of the detector is defined.

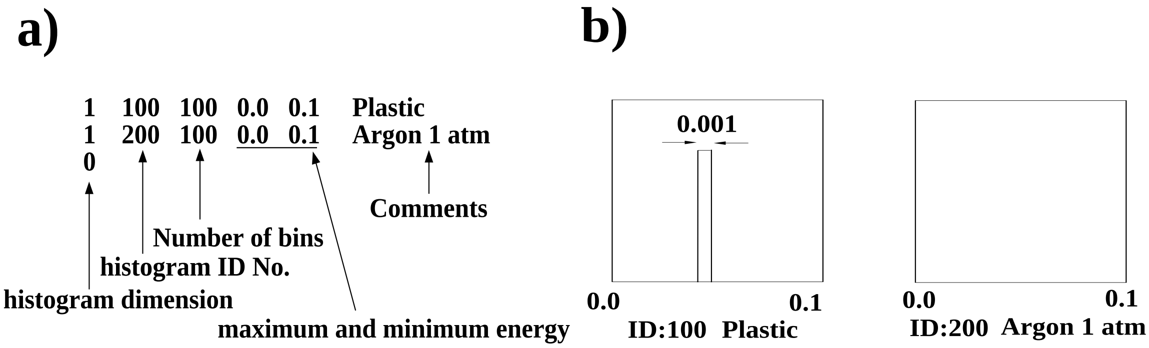

Figure 5: Fig(a) shows an example of histogram file. Fig(b) shows histograms correspond to the example of histogram file.

One row corresponds to a histogram for one part of the detector. The first column shows the dimension of histogram. In the case of the histogram for energy spectrum, the number of 1 should be written. The number in the second column is identification number of histogram. The number in the third column shows the number of bins in x axis. The fourth and fifth numbers correspond to minimum value and maximum value in x axis. In the sixth column, the comment is written. The number of 0 in the third row is a mark which shows the end of the definition. If users want to only obtain the information about energy spectrum of each parts in the detector, you do not have to rewrite any program or recompile it. It is only required for users to carry out the below procedure.

```
%egsanl
Input geometry file: ?test.geo
```

```
Input PEGS data file: ? material.dat
kind of particle e:-1 gamma:0 e:1 ? 0  ! 0 means X ray.@
x center:? 0.0
y center: ? 0.0   ! position to injection the particles
z center: ? 0.85
x range: ? 0.0
y range: ? 0.0    !  range of the incident particles
z range: ? 0.0
x direction: ? 0.0
y direction: ? 0.0    !  vector of incident direction
z direction: ?-1.0
Polarization vector x: ? 1.0
Polarization vector y: ? 0.0    !  polarization vector of incident X ray
Polarization vector z: ? 0.0
incident energy [MeV]: ? 0.1
Do you make histogram  (Y/N): ?Y
idim: 1 ? @temp.his    !  temp.his is histogram filename.
Input initial random number: ? 12345679
Number of particle: ? 10000    !  number of injected particles
  ----Simulation is started----
input HBK filename: ? temp.hbk    !  histogram data is saved in temp.hbk file
```

By this procedure, the histograms are saved in the file of `temp.hbk`. Users can check the results with the program of `dis45`[10].

2.4 Tests of the program

By obtaining several histograms, we checked the developed EGS4 program. Preparing for a geometry file for plastic scintillator, we had simulations by injecting 30 keV X rays polarized parallel to x axis from the direction of -z axis. Fig.6 shows the distribution for ϕ direction of scattered X rays by Compton scattering for the original EGS4 code and the developed EGS4 code. In this Figure, the x axis and y axis correspond to ϕ of the azimuthal angle and number of events, respectively. As shown in this figure, the maxima for number of events are observed at the azimuthal angle of 90° and 270°. The results are consistent with the equation for the cross section of Compton scattering. We also had similar simulation for Rayleigh scattering, and obtained the similar results to Compton

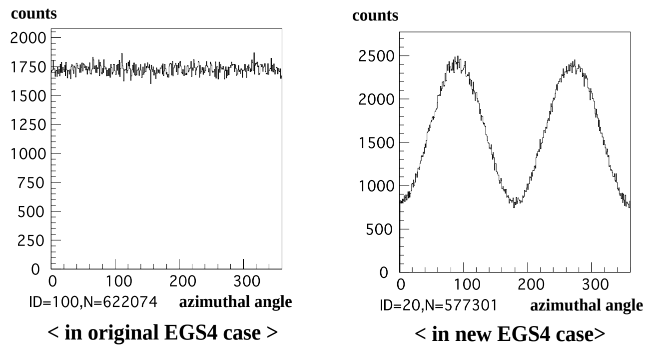

Figure 6: The distribution of azimuthal angle for scattered X rays by Compton scattering. The left and the right figures correspond to simulation for the original EGS4 code and the developed EGS4 code.

scattering. At second, using the same geometry file, we investigated the distribution of the azimuthal angle for emitted photoelectrons by photoabsorption. The results for the original EGS4 code and the developed EGS4 code are shown in Fig.7. From the equation of the cross section for photoabsorption, the maxima of number of events are expected to be at 0° and 180°. So the distribution in this figure is consistent with the equation of the cross section for photoabsorption. Finally, we had two simulations

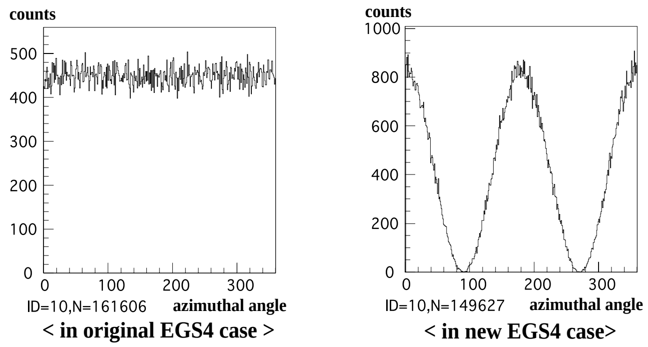

Figure 7: The distribution of azimuthal angle for emitted photoelectrons by photoabsorption. The left and the right figures correspond to simulation for the original EGS4 code and the developed EGS4 code.

to check the program for fluorescence yield. For one simulation, preparing for a geometry file of a detector made of lead (Z=82), X rays with the energy of 100 keV were injected to the detector. For the other one, preparing for a geometry file of a detector made of argon gas (Z=18) at 2 atm, X rays with the energy of 20 keV were injected to the detector. For each case, the fluorescence yields were calculated from the results of the simulations. In table.1, the fluorescence yields for each case are summarized. As shown in this table, the results of the simulations have good agreements with the data for the experiment.

Table 1: The comparison of fluorescence yields obtained from the simulations with them from the data for the experiment.

	lead	argon gas
Simulation	97%	11%
Experiment	95%	8∼ 10%

3 Application to Gas Counter

We have been developing an X-ray polarimeter in use of Gas Proportional Counter with MicroStrip, sensitive to the energy range from 20 keV to 40 keV[7][8][9]. Fig.8 shows the schematic view of the MSGC as X-ray polarimeter. As incident X rays come to the chamber, the X ray is photoabsorbed and

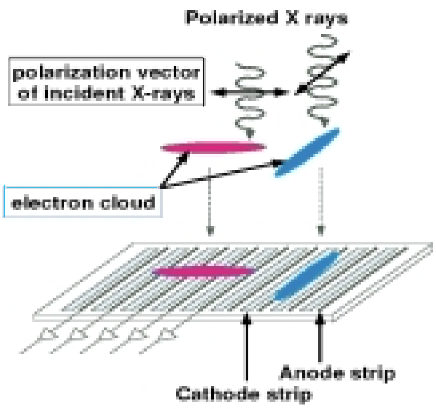

Figure 8: Schematic view of the MSGC as X-ray polarimeter.

photoelectron is emitted. Then the photoelectron ionizes gas molecule and electron cloud is created. Since the photoelectron tends to be emitted to the same direction as the polarization vector of the incident X ray, the shape of electron cloud extends to the polarization direction of the incident X ray on the average. Then it is drifted on the several anode strips, keeping the shape of the electron cloud. In the case that the polarization vector of the incident X ray is perpendicular to the anode strips, the number of anode strips with charge signal is more than that in the case that it is parallel to them. Thus it is in principle possible to detect the polarization by counting anode strips with charge signal. To check the principle, injecting 22keV polarized X rays parallel to x axis to argon gas at 1 atm, the extension of electron cloud for the two directions of x and y is simulated. Fig.9 shows the difference of the length of electron cloud.

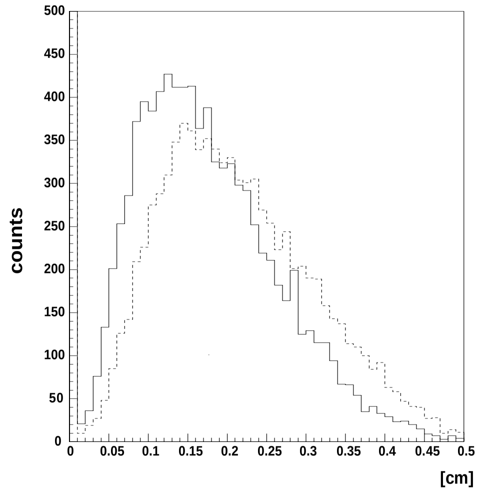

Figure 9: The x axis and y axis correspond to the extension of electron cloud for 22keV polarized X rays and the number of events, respectively. The solid line and the dashed line correspond to the extension for the directions of x axis and y axis, respectively.

4 Conclusion

We have improved EGS4 code to simulate polarized X rays with low energies by applying formulae for cross sections of photoabsorption, Compton scattering, and Rayleigh scattering in consideration of X-ray polarization. Moreover, fluorescence yields for K-shell were also supported in the code. The code is written with Fortran and users do not have to recompile the code even if geometry of the detector is changed. We had computer simulation with this code to investigate the characteristics of the MSGC polarimeter developed by us. Consequently, we confirmed that the shape of electron cloud depend on the polarization direction of the incident X ray. Therefore it is possible to detect the polarization by using MSGC. In the future we will use EGS4 to develop a X-ray polarimeter.

Acknowledgements

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