Physics process validation of Geant4 (Draft)

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1 Introduction

We have investigated the validity of our simulator. The validation item that we have already performed are summarized as follows.

1. Whether the energy loss distribution follows the Landau's distribution.
   - thin absorber of Silicon
2. Whether the energy loss along per unit length follows the formula of Bethe-Bloch for protons.
   - thick absorber of Silicon
   - thick absorber of Lead

2 Landau's distribution

To cheak out the Landau distribution, we made the thin slab of a silicon and injected protons into the slab in the simulation as shown in Figure 1.

Whether the energy loss distribution obeys the Gaussian or the Landau distribution depends on the ratio between the mean energy loss and the maximum energy transfer allowable in a single collision. The ratio is expressed as[1],

$$\kappa = \overline{\Delta}/W_{max} \tag{1}$$

$$where \qquad \overline{\Delta} \simeq 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} (\frac{z}{\beta})^2 \tag{2}$$

$$and \qquad W_{max} \simeq 2 m_e c^2 \eta^2 \tag{3}$$

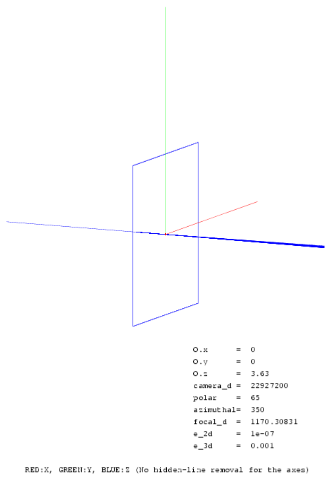

Figure 1: Physics process validation of Geant4 simulation.

The thin absorber region is generally taken to be $\kappa \ll 1$. we took $\kappa = 0.01$ and run Geant4 simulator for various energy,fitted the obtained energy loss distribution using ROOT, and compared the obtained most probable energy loss with that of theoretical value, calculated as follows[1]

$$\Delta_{mp} = \overline{\Delta}[ln(\overline{\Delta}/\varepsilon) + 0.198 - \delta] \tag{4}$$

$$ln\varepsilon = ln\frac{(1-\beta^2)I^2}{2mc^2\beta^2} + \beta^2 \tag{5}$$

where δ is the density effect. These result is shown in Figure 2 and Table 1.

3 Bethe-Bloch Formula

We constructed the silicon and lead slab in the simulation and injected protons into the slab to validate the Bethe-Bloch formula. The thickness of the slab was determined so that $\kappa = 3$.

For Comparison between the energy loss of Geant4 data and that of the theoretical value, we used “The Stopping and Range of Ions in Matter 2000 (SRIM2000)“, which is a free software developed by IBM, to get the energy loss of the theoretical value. The results are shown in Figure 3, Table 2 and 3.

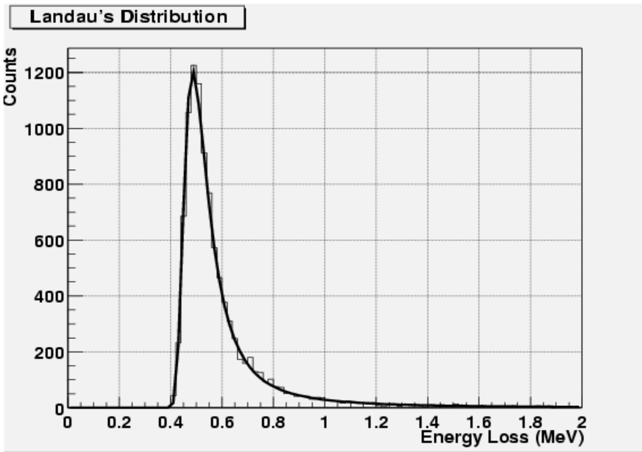

Figure 2: Histogram of the energy loss when the 1GeV proton injected into the thin silicon absorber.

Table 1: Result of the comparison between Geant4 data and theoretical values when the absorber is silicon.

particle energy	thickness (cm)	Δ_{mp} (Geant4)	Δ_{mp} (Theoretical Value)	difference between data and theo. [%]
1MeV	2.60×10^{-7}	14.35 ± 1.84 eV	14.50 eV	-1.0
5MeV	6.48×10^{-6}	450.6 ± 3.7 eV	424.0 eV	5.9
10MeV	2.58×10^{-5}	1.244 ± 0.007 keV	1.154 keV	7.3
50MeV	6.19×10^{-4}	10.16 ± 0.03 keV	9.448 keV	7.0
100MeV	2.36×10^{-3}	24.20 ± 0.06 keV	22.48 keV	7.1
500MeV	4.45×10^{-2}	184.2 ± 0.3 keV	179.5 keV	2.6
1GeV	1.44×10^{-1}	492.9 ± 0.7 keV	486.9 keV	1.2
10GeV	7.68	28.79 ± 0.04 MeV	28.02 MeV	2.7

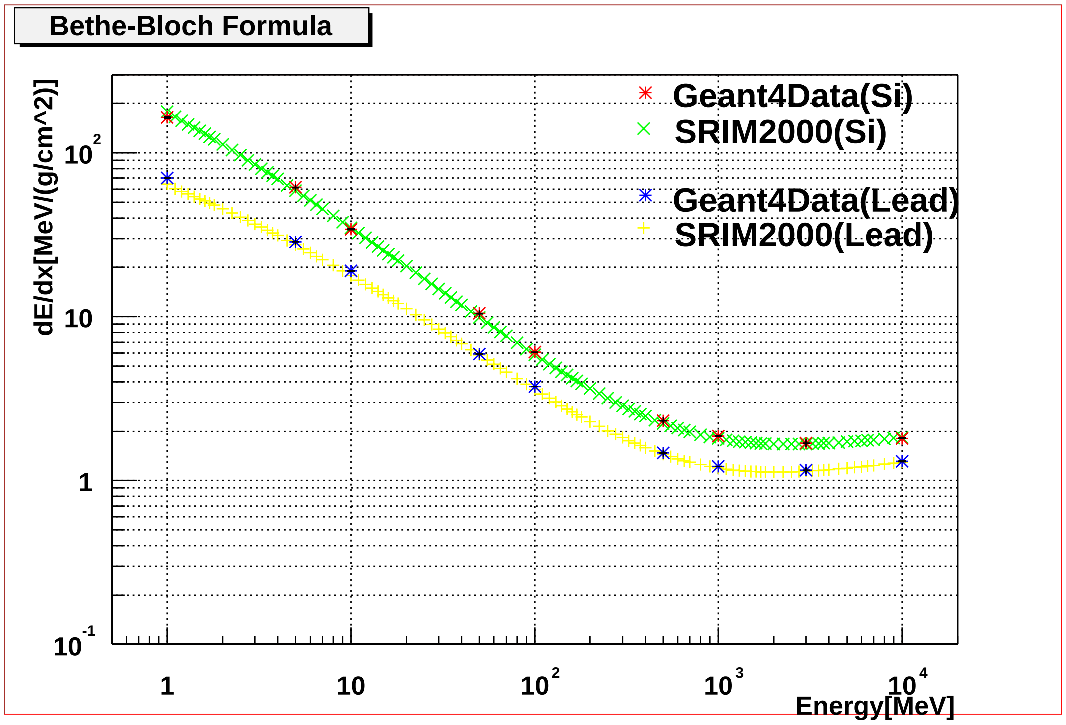

Figure 3: Energy loss calcurated by SRIM2000 and the result of the Geant4 simulation.

Table 2: Result of the comparison between Geant4 data and theoretical values when the thick absorber is silicon. All κ are 3 except for 3 and 10 GeV proton.

particle energy	thickness (cm)	$\frac{dE}{dx}$ [MeV/(g/cm^2)] (Geant4)	$\frac{dE}{dx}$ [MeV/(g/cm^2)] (SRIM2000)	difference between data and theo. [%]
1MeV	7.00×10^{-4}	164.4 ± 1.4	178.2	-7.7
5MeV	1.94×10^{-3}	61.46 ± 0.12	58.69	4.7
10MeV	4.00×10^{-3}	34.13 ± 0.29	34.81	-1.9
50MeV	1.87×10^{-1}	10.46 ± 0.02	9.899	5.6
100MeV	7.08×10^{-1}	6.068 ± 0.009	5.859	3.6
500MeV	1.33×10	2.317 ± 0.016	2.236	3.6
1GeV	4.30×10	1.868 ± 0.041	1.805	3.5
3GeV	70.0 ($\kappa = 0.78$)	1.692 ± 0.006	1.671	1.3
10GeV	44.0 ($\kappa = 0.06$)	1.810 ± 0.008	1.834	-1.3

Table 3: The same as the table 2, but for lead sheet.

particle energy	thickness (cm)	$\frac{dE}{dx}$ [MeV/(g/cm^2)] (Geant4)	$\frac{dE}{dx}$ [MeV/(g/cm^2)] (SRIM2000)	difference between data and theo. [%]
1MeV	2.02×10^{-5}	70.17 ± 0.18	64.27	9.2
5MeV	5.03×10^{-4}	28.64 ± 0.07	27.42	4.4
10MeV	2.00×10^{-3}	19.05 ± 0.04	17.78	7.1
50MeV	4.80×10^{-2}	5.926 ± 0.011	5.838	1.5
100MeV	1.83×10^{-1}	3.747 ± 0.006	3.588	4.4
500MeV	3.45	1.471 ± 0.001	1.448	1.6
1GeV	1.11×10	1.217 ± 0.001	1.192	2.1
3GeV	69.7 ($\kappa = 1$)	1.155 ± 0.003	1.140	1.3
10GeV	19.9 ($\kappa = 0.1$)	1.309 ± 0.009	1.291	1.4

4 Result

We investigated the physics process validity of Geant4 in terms of the energy loss. In the reproduction of the Landau distribution, the diffrence between the most probable energy loss of the Geant4 data and that of theoretical value is small. About Bethe-Bloch, the Geant4 data is consistent with the theoretical value, except for the 1MeV proton injected into both the silicon and the lead slab. The difference between the Geant4 data and the theoretical value are larger than others ($< 10\%$).

5 Future Plan

- Confirmation of the equation used in SRIM2000
- Landau distribution of the energy loss in a lead slab
- Low energy option of Geant4.3.0

References

[1] William R. Leo, Techniques for Nuclear and Particle Physics Experiments, 1994