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FLUKA Simulation of Cosmic Muon-Induced Energy Deposition in Pb, Cr, Fe, Sb, and Ni Metals at Various Energies

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Abstract

In this study, the energy depositions caused by cosmic muons with energies of 2, 3 and 4 GeV were investigated using FLUKA simulation program. The energy depositions were examined in Pb, Cr, Fe, Sb, and Ni metals with dimensions of 100x100 cm^2, and thicknesses of 20, 40, 60, 80, and 100 cm. The simulations revealed that cosmic muons of different energy levels have varied impacts on the energy deposition. Furthermore, the effect of the metal type and thickness on the deposited energy values was investigated and it was observed that it increased proportionally depending on the thickness.

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Keywords

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Highlights

Energy Deposition of Cosmic Muons in Metals.
Interaction of Cosmic Muons with Matter.
Metals Suitable for Shielding.
Cosmic muon imaging technology

Çeşitli Enerjilerde Pb, Cr, Fe, Sb ve Ni Metallerinde Kozmik Müonlar Tarafından Oluşturulan Enerji Birikiminin FLUKA Simülasyonu

Özet

Bu çalışmada, FLUKA simülasyon programı kullanılarak; 2, 3 ve 4 GeV enerjili kozmik müonların 100x100 cm^2 *boyutlarında ve 20, 40, 60, 80 ve 100 cm kalınlıktaki Pb, Cr, Fe, Sb ve Ni metallerinde oluşturduğu enerji birikimleri incelenmiştir. Simülasyonlar, farklı enerji seviyelerindeki kozmik müonların enerji depolanması üzerinde farklı etkileri olduğunu ortaya koymuştur. Ayrıca metal türü ve kalınlığının depolanan enerji değerleri üzerindeki etkisi incelenmiş, kalınlığa bağlı olarak orantılı bir şekilde arttığı gözlenmiştir.*

Anahtar Kelimeler

Kozmik Müon, Depolanan Enerji, FLUKA, Monte Carlo

Öne Çıkanlar

Kozmik müonların metaller üzerindeki enerji depolanması. Kozmik müonların madde ile etkileşimi. Zırhlama için kullanılabilecek metaller. Kozmik müonlar ile görüntüleme teknolojisi

1. Introduction

The Earth, along with other celestial entities such as planets and satellites, is constantly bombarded by high-energy particles and nuclei coming from many sources in the universe. These sources include stars and astronomical phenomena such as supernovae. These particles are commonly referred to as "primary cosmic rays." If a planet has an atmosphere, primary cosmic rays interact with the atoms or molecules in the atmosphere through a variety of nuclear reactions that differ depending on the type of atmospheric gases present. Such nuclear interactions cause cascades of particles, resulting in a particle shower.

These nuclear reactions give rise to cascades where numerous particles are produced, forming a particle shower. The first interaction with the atmosphere results in the production of neutrons, protons and electrons, at approximately 25 km above sea-level. After secondary collisions, neutrons and pions are produced, at the during cosmic shower the maximum secondary particle rate is reached at a altitude of approximately 12 km [1]. Most of the new particles produced are pions and predominantly neutral pions decay into two photons.

$$\pi^0 \rightarrow \gamma + \gamma$$

There are also other neutral pion decay modes, a few examples are given below [2];

$$\pi^0 \rightarrow e^+ + e^- + \gamma$$

$$\pi^0 \rightarrow e^+ + e^+ + e^- + e^-$$

Charged pions also may interact with nucleus of the air. Therefore they contribute to the cosmic shower by producing muons and neutrinos [3];

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

The high-speed cosmic muons (0.94c-0.98c) that can reach the Earth's surface are referred
to as "secondary cosmic rays"[4].

Most cosmic muons are produced in the high altitudes of the atmosphere (approximately 15 km), and, as a result of their interactions with atmospheric atoms, they lose about 2 GeV of energy before reaching the Earth's surface. The average energy of cosmic muons at the Earth's surface is approximately 4 GeV [5]. Also, muons arrive at sea level with an average us of about one muon per square centimeter per minute [6].

One of the main applications of cosmic muons is imaging technology [6-10]. In comparison to other particles, cosmic muons are very penetrating due to their weak interaction with materials, large mass, and high energy.

This characteristic enables imaging technologies utilizing cosmic muons to yield much better results than others. There are two techniques for muon imaging. One method is muon absorption imaging, based on the energy loss mechanism of muons travelling through the material. In this case, the deposited energy in the medium is crucial.

In this study, the average energy values deposited in the medium as a result of the interaction of 2, 3 and 4 GeV energy muon beams with four different metals (Pb, Cr, Fe, Sb, Ni) were calculated using the FLUKA simulation code.

1.1. The average energy loss of cosmic muons

While muons pass through a medium, they lose their energy through interactions such as ionization, pair production, bremsstrahlung, muon decay and nuclear interaction. Their primary energy lose mechanism is ionization for dense matter and the average energy loss is described by the Bethe-Bloch Formula (Eq. 1) [11].

$$-\langle\frac{dE}{dx}\rangle = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_ec^2\beta^2\gamma^2\,T_{max}}{\mathrm{I}^2}\right)-\beta^2-\frac{\delta\,(\beta\gamma)}{2}\right] \tag{1}$$

where,

T_{max} : maximum energy which can be transferred to a free electron in a single collision.

N_A : Avagadro number, r_e : classical radius of the electron (2.8 fm),

m_e : electron mass, A : atomic mass of the medium, β (v/c), γ $(1-\beta^2)^{-2}$: relativistic constant,

z: charge of the incident particle,

Z : atomic number of the medium, I : mean excitation energy of medium

δ : density correction term.

2. Material and Method

2.1. FLUKA simulation program

FLUKA is an advanced simulation program that utilizes the Monte Carlo technique for particle transport and interactions with matter. It has various application areas, including nuclear shielding, dosimetry calculation, detector design, accelerator-driven systems, high-energy particle interactions with matter, cosmic rays, neutrino physics, and radiotherapy.

FLUKA can simulate the interaction and propagation of 60 different particles with high accuracy. The energy of these particles can range from 1 keV to thousands of TeV. It includes muons of various energies, hadrons with energies up to 20 TeV, their corresponding antiparticles, thermal neutrons, and heavy ions.

The program allows for the simulation of diverse studies in these fields, providing detailed insights into the behavior of particles and their interactions with matter [12,13]. FLUKA is written in FORTRAN 77 and features a user-friendly interface called Flair.

Flair is developed using the Python programming language. With the Flair interface, the system to be simulated can be visualized in 2D and 3D. Furthermore, FLUKA provides a wide range of pre-defined materials to construct the simulated system. Optionally, users can create complex material structures with desired molecules, mixtures, alloys, etc. [14].

2.2 System design

The axes were denoted as X, Y, and Z in the FLUKA input file. In the XY plane, the material's surface is 100x100 cm^2, and the thickness of the material is defined as a range of 20-100 cm along the Z-axis. The pencil muon beam is directed along the Z axis, precisely at the center of the XY surface of the material. The FLUKA interface Flair image is given in Figure 1.

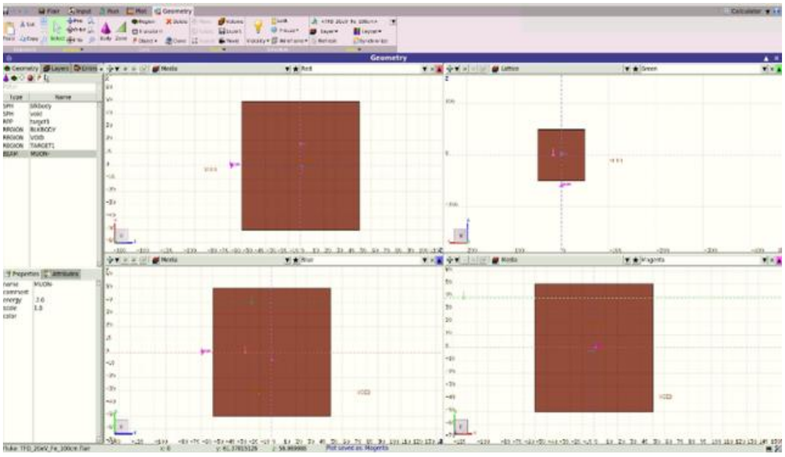

Figure 1. Overview of the Flair Interface.

The FLUKA program was performed with ten cycles for the 10^5primary particles (muons) to increase statistical accuracy. In the simulation, Pb, Cr, Fe, Sb, and Ni metals of five different thicknesses (20, 40, 60, 80, and 100 cm) were used. Their properties are given in Table 1. Each material was exposed to a pencil muon beam with 2, 3, and 4 GeV energies, and the deposited energy values by the muons were calculated depending on the thickness of the metals. For this purpose, the USRBIN card was used in the FLUKA input file, and deposited energy values in the material per unit volume and primary particle (muons) were determined.

Table 1. Z and ρ (g/cm^3) values of the elements examined in this work.

Element	Z	ρ (g/cm^3)
Pb	82	11.3
Ni	28	8.90
Fe	26	7.87
Cr	24	7.19
Sb	51	6.69

3. Results

The deposited energy values by muons passing through each metal with five different thicknesses calculated with the FLUKA simulation code are given in Table 2-4. The statistical error range for the computed energy deposition values is between 0.8% - 2%. Upon examining the data in the tables, it is evident that the amount of deposited energy is dependent not only on the density of the material but also on its thickness.

The deposited energy value within the material is dependent on the thickness and the type of the material. As expected, due to its high atomic number and density, lead (Pb) has the largest amount of stored energy among the metals investigated in this work. Despite having a higher atomic number (Z) than chromium (Cr), iron (Fe), and nickel (Ni), antimony (Sb) has the least stored energy since its density is lower than the other three elements.

When the energy values of muons with three different energies are evaluated in the same metal with the same thickness, it becomes apparent that there is no significant difference between them. Figures (2-4) show the variations in deposited energy values as a function of metal thickness for each muon energy.

Table 2. Energy deposition values (GeV/cm^3/Primary) caused by 2 GeV muons.

Elements	**20 cm**	**40 cm**	**60 cm**	**80 cm**	**100 cm**
Pb	0.307887	0.613203	0.912521	1.204621	1.488678
Cr	0.237785	0.477060	0.713142	0.945811	1.173407
Fe	0.260667	0.522276	0.779598	1.032430	1.279272
Sb	0.197912	0.397009	0.594249	0.788771	0.980762
Ni	0.299467	0.598542	0.891784	1.178164	1.456475

Table 3. Energy deposition values (GeV/cm^3/Primary) caused by 3 GeV muons.

Elements	**20 cm**	**40 cm**	**60 cm**	**80 cm**	**100 cm**
Pb	0.322272	0.644783	0.963935	1.277111	1.584597
Cr	0.245282	0.495428	0.743541	0.989339	1.231887
Fe	0.269288	0.543247	0.813638	1.081986	1.346104
Sb	0.205367	0.415116	0.622551	0.828291	1.032123
Ni	0.310322	0.623581	0.933736	1.239370	1.539711

Table 4. Energy deposition values (GeV/cm^3/Primary) caused by 4 GeV muons.

Elements	**20 cm**	**40 cm**	**60 cm**	**80 cm**	**100 cm**
Pb	0.332350	0.666376	0.998932	1.325954	1.650360
Cr	0.249913	0.507058	0.763088	1.017471	1.269145
Fe	0.274757	0.556817	0.836706	1.114899	1.390479
Sb	0.210381	0.426926	0.641304	0.855294	1.067189
Ni	0.317119	0.640462	0.960672	1.278989	1.593242

The graphs clearly illustrate the direct relationship between the deposited energy values within the material and the thickness and density of the material. In addition, the reported data was fitted with a linear fit function using $\mathcal{K}^2$ test in the CERN ROOT software [15]. The function is expressed as y = p0 + p1x, where y is the deposited energy and p0 and p1 are the fit parameters, the values of which are displayed on the graphs. For each metal, there are five data points to be matched. However, two of them (p0 and p1) are not free-fit parameters. Therefore, the number of degrees of freedom presented in the figures is three (ndf = 3).

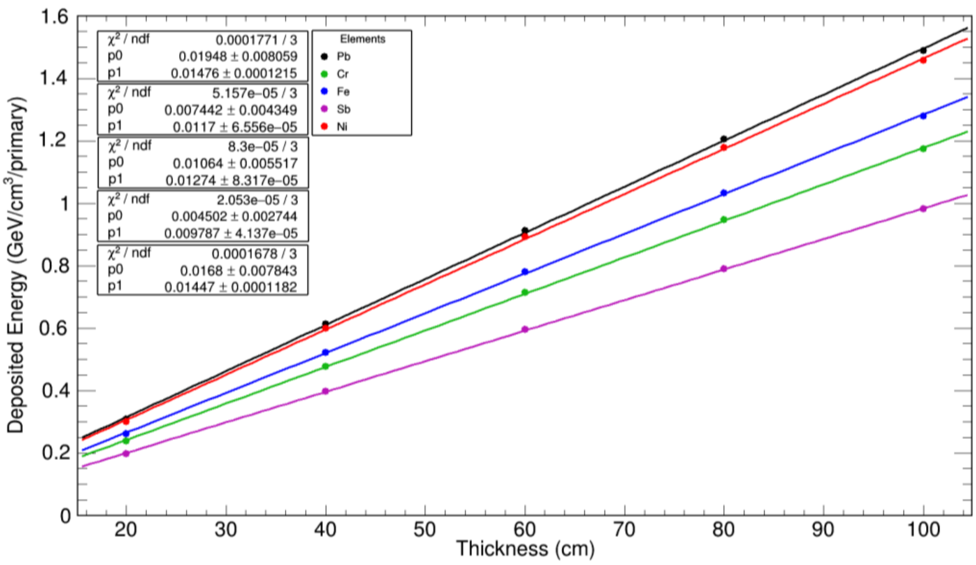

Figure 2. Deposited energy of 2 GeV muons in five different metals with varying metalthickness. The lines are the fits of the data plotted with a function y=p0+p1 for the eye track.

The material with the highest energy storage value is Pb, while the material with the lowest is Sb, as shown in Figure 2. A similar trend can be seen in Figures 3 and 4.

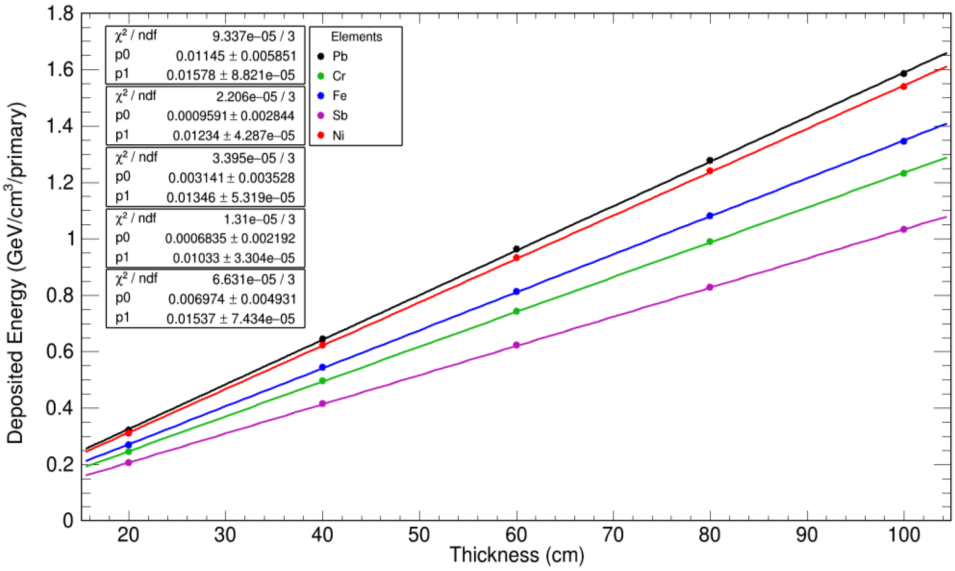

Figure 3. Deposited energy for 3 GeV muons.

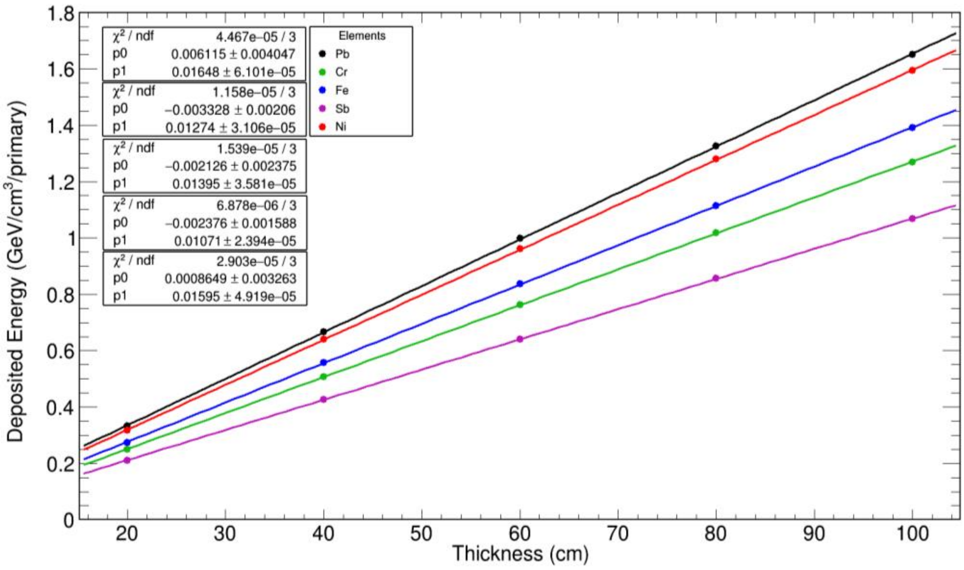

Figure 4. Deposited energy for 4 GeV muons.

Lead (Pb) absorbs a considerable amount of the energy of charged heavy particles. This characteristic makes Pb and Pb-based alloys suitable for shielding purposes in nuclear power plants [11]. Stopping the heavy particles, like muons, can be highly challenging. Therefore, it is helpful to use muon absorption imaging techniques. However, it may be sufficient to attenuate lower-energy light particles or photons.

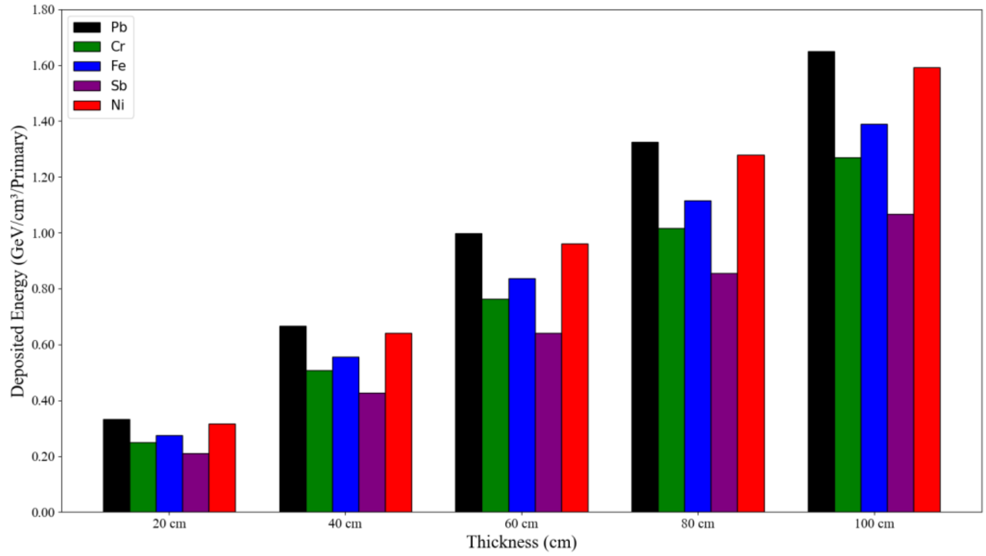

Figure 5. The comparison of deposited energy by 4 GeV muons for the metals investigated in this work.

Figure 5, a column chart, shows a comparison of deposited energy values simulated by the FLUKA for the studied metals at 4 GeV muon energy. It is clear that Pb has the greatest amount of energy storage, followed closely by Ni.

The normalised percentage increase in energy deposited as a function of metal thickness is given in Table 5. The data for 20 cm thickness is used as a reference for normalisation.

In the increment of thickness from 20 cm to 100 cm, lead (Pb) exhibits the smallest percentage increase in stored energy, while antimony (Sb) demonstrates the highest. However, this differences are not significant, it would not be right to make a clear comment. Additionally, lead (Pb) and Pb-based metal alloys are extensively utilized in nuclear shielding applications due to their density advantage.

Table 5. The normalised percentage increase in energy depositions investigated in this work. The data for each metal is normalised with is 20 cm thickness results.

Energy : 2 GeV					
Thickness	**Pb**	**Cr**	**Fe**	**Sb**	**Ni**
20 cm	-	-	-	-	-
40 cm	99.165%	100.627%	100.361%	100.599%	99.869%
60 cm	196.382%	199.910%	199.078%	200.259%	197.790%
80 cm	291.254%	297.759%	296.072%	298.546%	293.420%
100 cm	383.514%	393.474%	390.769%	395.555%	386.356%
Energy : 3 GeV					
Thickness	**Pb**	**Cr**	**Fe**	**Sb**	**Ni**
20 cm	-	-	-	-	-
40 cm	100.074%	101.983%	101.735%	102.134%	100.946%
60 cm	199.106%	203.137%	202.144%	203.141%	200.893%
80 cm	296.284%	303.348%	301.795%	303.322%	299.382%
100 cm	391.696%	402.233%	399.875%	402.575%	396.166%
Energy : 4 GeV					
Thickness	**Pb**	**Cr**	**Fe**	**Sb**	**Ni**
20 cm	-	-	-	-	-
40 cm	105.504	102.894%	102.658%	102.930%	101.963%
60 cm	200.566%	205.341%	204.526%	204.830%	202.937%
80 cm	298.963%	307.130%	305.776%	306.545%	303.315%
100 cm	396.573%	407.835%	406.076%	407.265%	402.411%

4. Conclusion

This study calculated the deposited energy by muons with 2, 3 and 4 GeV energies while passing through 5 different metals (Pb, Cr, Fe, Sb, Ni) with the FLUKA code. Based on the results obtained from the FLUKA simulation program, it is observed that lead (Pb) exhibits the highest energy deposition value, making it the most suitable metal for applications such as nuclear shielding and muon absorption imaging. In addition, Ni or Pb-Ni based alloys are found to be other good candidates as the most suitable metals to be used. The simulation results of the presented study provide qualified information for further research in the same working field.

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Conflict of Interest:
There is no conflict of interest

Author Contribution:
Each author has an equal share.

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