Cross section simulation using Monte Carlo Glauber model for Space Radiation Protection

Dylan Delgado
Department of Physics and Astronomy, University of California, Davis

As space exploration advances, understanding the impact of Galactic Cosmic Rays (GCRs) on spacecraft and astronaut safety is crucial. This paper proposes a novel approach, to simulate GCR interactions using carbon, silicon, aluminum, nickel, and iron as targets. Practical constraints led to the exploration of nickel and aluminum as alternative materials. Employing the Monte Carlo Glauber calculation model, we conducted simulations, comparing particle cross-sections resulting from material substitutions. Our study contributes to refining strategies for future space missions, offering insights into effective shielding against high-energy GCRs.

I. INTRODUCTION

As space exploration advances, the necessity of comprehending space radiation's impact on spacecraft, electronics, and astronaut safety becomes increasingly evident. Our knowledge is currently bounded by the capabilities of existing facilities, which cover particle energy ranges up to 1.5 GeV per nucleus. However, the challenge lies in Galactic Cosmic Rays (GCRs), characterized by energy levels surpassing 100 GeV and encompassing particles from protons to iron nuclei. Understanding the damage potential across various energy levels, intricately linked to atomic numbers squared, is vital for effective shielding.

Here we describe a collaboration at the Relativistic Heavy Ion Collider (RHIC) Brookhaven National Laboratory, a proposed approach involves employing carbon, silicon, and aluminum as targets, utilizing beams of carbon, silicon, and iron to explore the effects of GCRs.Despite its suitability, silicon is too brittle for use as a target, while iron's ferromagnetism presents unsuitability for the intended purpose. On the other hand, Nickel, with its comparable atomic number to iron yet diminished ferromagnetism, arises as a feasible substitute. Similarly, aluminum's structural similarities to silicon position it as a pragmatic alternative.

Central to our investigation is the accuracy of these material substitutions compared to the ideal choices. Thus, our paper aims to simulate particle collisions, extract particle cross-sections, and rigorously compare them with nucleon collisions. Evaluating the approximation level in substituting Ni+Fe for Fe+Fe and Al+Al for Si+Al collisions, our objective is to assess the validity of these material selections. This scrutiny will significantly contribute to refining our understanding of space radiation effects, aiding in the formulation of more effective strategies for future missions.

II. TECHNICAL BACKGROUND

Our study employs the Monte Carlo Glauber calculation model, renowned for its efficacy in studying heavy ion collisions. The Glauber model functions on the principle that interactions between nuclei are a composite result of individual nucleon-nucleon collisions. This approach allows us to treat these collisions akin to proton-proton collisions, particularly at heightened energies where protons and neutrons become indistinguishable.

The parameters constituting our model are detailed in Table I. Utilizing a Wood-Saxon distribution (as expressed in Equation 1 and depicted in Fig. 1), these parameters form the basis for determining the density distribution essential for constructing the nucleus of each element and executing the collision simulation experiment.

TABLE I: Wood-Saxon Parameters for Elements of Interest

Element	**Radius (fm)** (R)	**Skin depth (fm)** (d)
Silicon	3.07	0.519
Aluminum	3.14	0.537
Nickel	4.11	0.52
Iron	4.31	0.517

The density distribution determined by the Wood-Saxon distribution, as expressed by Equation 1:

$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r-R}{a}\right)} \tag{1}$$

Here, $\rho(r)$ signifies the density at a radial distance r, ρ_0 represents the central density, R denotes the radius parameter, and a symbolizes the skin depth.

The next crucial step in our methodology involves determining the nucleon-nucleon collision parameters. These collision properties are quantified by the nucleon cross-section, reported as 42 mb at $\sqrt{S_{NN}} = 200\,\text{GeV}$ [1],[2]. This cross-section measurement enables us to calculate the requisite proximity of two nucleons in the x and y planes to qualify as a collision, as expressed by Equation 2:

$$d_{\text{collision}} = \sqrt{\frac{\sigma_{\text{NN}}}{\pi}} \tag{2}$$

Here, $d_{\text{collision}}$ represents the distance required for a nucleon-nucleon collision, and σ_{NN} denotes the nucleon-nucleon cross-section.

The accurate determination of nucleon-nucleon collision parameters serves as the foundational basis for executing the subsequent collision simulation experiments, crucial in our investigation of heavy ion interactions.

Fig. 2 is a representation of one of our simulated collisions. We can see how we have the ability to determine the number of total nucleon collisions and the number of participants in

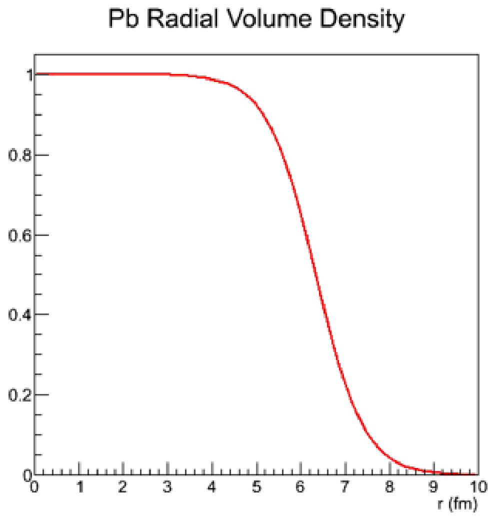

FIG. 1: Wood-Saxon density plot for Lead with parameters R = 6.34 fm and a = 0.54 fm (Notice the density reaches half of the central density when Radius parameter

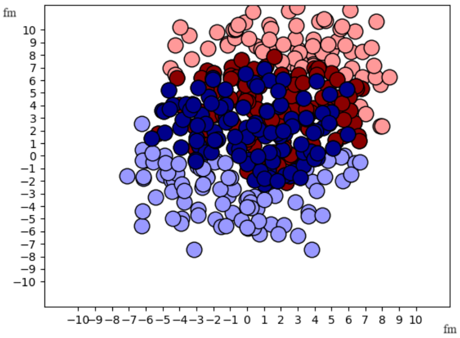

FIG. 2: Here we have a simulation of two gold nucleus colliding with an impact parameter of 5 fm, viewed in the transverse plane. The dark colored nucleons are the ones that were determined to have collided.

our simulation. These are not observables in experiment but are the basis of the Monte Carlo Glauber Model and are what allow us to determine centrality's of collisions and how many particles might be created in the process.

Fig.3 shows the range for impact parameter for a given nucleus-nucleus collision. It shows how the most common types of collisions are the most peripheral, which is caused by the increase in area. This gives us intuition for what we call N_{coll} distribution should look like. N_{coll} is the number of nucleon-nucleon collisions in each nucleus-nucleus collision. Having the most common collisions at high impact parameter around which would translate into more common low N_{coll}.

We can calculate nucleus-nucleus cross section based on the flux of particles and the hit rate. In our simulation we fix the number of nucleus that are created in a uniform distribution over a known area that we set well over an impact parameter where there are no collisions. That will give us our flux and we can get our hit rate by how many nucleus-nucleus collisions happened by setting out count with a minimum of 1 nucleon-nucleon collision.

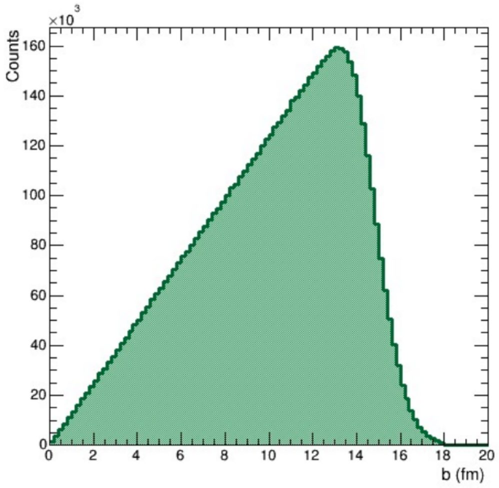

FIG. 3: This figure shows the count distribution of nucleus nucleus collisions, with a centered lead nucleus and a smooth distribution of lead nuclei

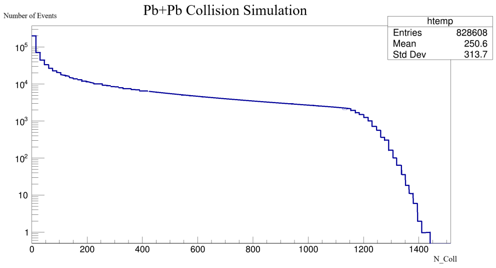

FIG. 4: N_{coll} distribution of Pb+Pb nucleus collisions

We can see in Fig 4. that our intuition from the impact parameter distribution was correct. Now when we compare our collisions of interest we can qualitatively see how their nucleon distributions compare quantitatively compare their cross-sections and calculate their difference. They can also be used as a correction factor if actual data of these collisions is taken.

III. RESULTS

TABLE II: Collision Cross-Sections and differences

Nucleus Collision	**Cross Section (b)**	**Difference (%)**
Ni+Fe	2.949	2.7
Fe+Fe	2.869	
Al+Al	1.728	3.2
Si+Al	1.784	

Our N_{coll} distribution for Ni+Fe and Si+Al is shown by figures 5 and 6. Compared to the distribution for Lead we can see they taper off slower. This is because the ratio of skin parameter to radius for small Z nucleus is far larger and therefore are more diffused through space causing the longer tail. We can also qualitatively see the difference between them is very small which is what we expected. We can also calculate our cross-sections from the total nuclei that collided and the area we allowed the generation of $400\ \mathrm{fm}^2$. The calculated cross-sections are given by Table 2 and it is shown that the differences are well below 5% which is the standard error allowed for uncertainty causing mechanisms in these experiments. Furthermore since the differences are known there could be corrections performed on actual data collected in experiments to better approximate the collisions of interest. This however shows that the difference between these nucleon nucleon collisions are not a significant factor for error.

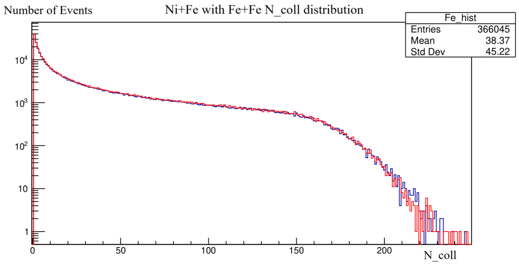

FIG. 5: N_{coll} distribution of Ni+Fe (red) and Fe+Fe (blue)

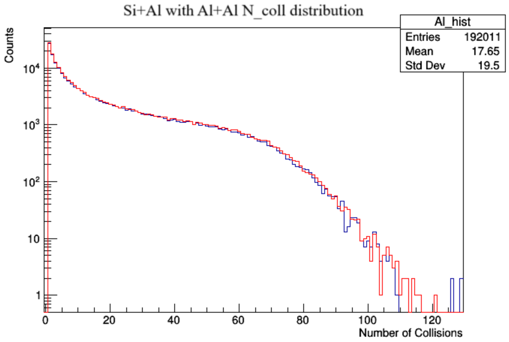

FIG. 6: N_{coll} distribution of Si+Al (red) and AL+Al (blue)

IV. CONCLUSION

In conclusion, our study delves into the effects of GCRs on spacecraft and astronaut safety, particularly focusing on the challenges posed by high-energy GCRs. In collaboration with RHIC Brookhaven National Laboratory, where a proposed approach utilizing carbon, silicon, aluminum, nickel, and iron as targets for simulating GCR interactions. The search for alternative materials led us to consider nickel and aluminum as practical substitutes, given their respective properties.

Implementing the Monte Carlo Glauber calculation model, we conducted simulations of particle collisions, extracting particle cross-sections and comparing them rigorously with nucleon collisions. The evaluation of material substitutions (Ni+Fe for Fe+Fe and Al+Al for Si+Al) aimed to assess the validity of these choices in understanding space radiation effects. Our findings contribute to refining strategies for future space missions.

V. ACKNOWLEDGMENT

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[1] Schwierz, N., Wiedenhöver, I., & Volya, A., ”Parameterization of the Woods-Saxon Potential for Shell-Model Calculations,” Journal of Nuclear Physics (2013).
[2] Miller, M. L., Reygers, K., Sanders, S. J., & Steinberg, P., ”Glauber Modeling in High Energy Nuclear Collisions,” Journal of Nuclear Physics, (2007).