An Analysis of Al+Al and Al+Si Nuclear Cross-Sections for Space Radiation Protection

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NASA has announced a series of new missions to the moon, titled the "Artemis" missions. These missions aim to build a permanent and functional space station on the moon. As with any mission to space, there is a multitude of problems that can (and will) arise and therefore must be adequately researched ahead of time. One of NASA's main concerns is the effects of long-term space radiation (Galactic Cosmic Rays) on astronauts, electronics, and the spacecraft (objects of interest). The STAR detector at RHIC has volunteered to provide these data to NASA. The proposal includes installing three targets (carbon, aluminum, and nickel) to act as the objects of interest, three beams (carbon, aluminum, iron) to act as the Galactic Cosmic Rays (GCRs), at three energies (5, 20, and 50 GeV) to simulate the varying energies of the GCRs. STAR swapped the Si-28 target with an Al-27 target (with the argument of a one-nucleon difference being negligible to the data NASA wishes to collect). Similarly, STAR added a Ni-58 target to act as the Fe-56 beam. In this paper, I quantitatively validate the substitutions by using the Glauber Model. The resulting data shows a difference of 3.2% in the nuclear cross-sections between Al+Al and Al+Si and a 2.7% difference for Fe+Fe and Fe+Ni. STAR's total systematic error is 5%. Therefore, these substitutions contribute less overall error to the experiment than the use of the detector itself. It is by this argument that I conclude the substitution of Al-27 for Si-28 and Ni-58 for Fe-56 to be valid.

I. INTRODUCTION

A. Background

In a brief definition, space radiation is any energetically charged particle in space. There are three main types: solar wind, solar energetic particles, and galactic cosmic rays (GCRs). The solar wind is the lowest in energy of the three types of radiation (0.5 to 10 keV). The "wind" is a continuous flow of protons from the surface of stars. Due to its low energy, this form of radiation can be stopped after a few micrometers in water. Therefore, it's not of much concern to NASA.

Solar energetic particles are more colloquially known as "solar flares". These are higher in energy than the solar wind (up to a few 100 MeV). It includes protons and ions whose range in water is up to tens of centimeters. Unlike the solar wind which is a constant emitter of radiation, the solar energetic particles are active in a cycle that's about thirteen years in length.

The third form of space radiation is the galactic cosmic rays (GCRs). These particles are the highest in energy of the three (2 - 50 GeV), resulting from high-energy space phenomena, such as supernovae. GCRs can travel hundreds of meters through water, and therefore cannot be shielded. Since NASA cannot shield astronauts, electronics, and spacecraft from GCRs, they need to know the long-term effects of GCR collisions with these objects of interest (OOI) to prepare for the missions adequately.

NASA has known that GCRs would be problematic for years. Consequently, they've done a full sweep of data measurements with various detectors in space (including Voyager, the ISS, balloons, etc.). They have also been collecting low-energy (less than 1 GeV) GCR data at facilities like the NASA Space Radiation Laboratory (located at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab) and tens of smaller cyclotron facilities. Crocker Lab at UC Davis is one of these facilities.

B. Space Radiation Project

NASA now needs to fill in the gaps of their GCR knowledge by collecting massive, high-energy data (2 - 50 GeV). These data are difficult to measure in space and expensive to collect on Earth because they require either of the two largest particle accelerators in the world: RHIC or the Large Hadron Collider (LHC).

The most abundant and massive elements that compose the GCRs are carbon, silicon, and iron (as shown in Figure 1). NASA does not have the collision data between these massive elements and the OOI.

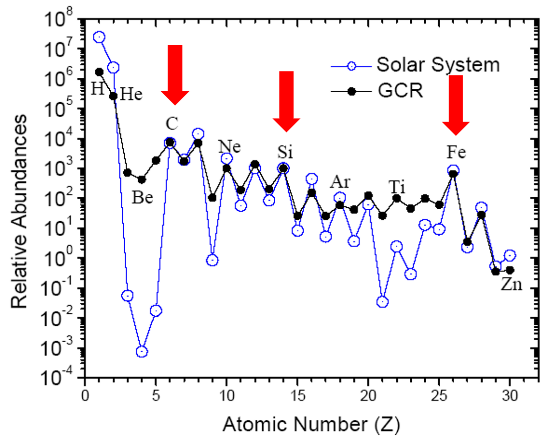

Figure 1: Relative abundances of the Galactic Cosmic Rays. The massive elements occurring high abundances are indicated by the red arrows [1].

To gather these data, NASA proposed the OOIs could be modeled as single elements: astronauts as carbon, electronics as silicon, and the spacecraft as aluminum. These three elements would act as the fixed targets in the accelerator, with the massive and abundant GCR elements being the beams fired at these targets. As aforementioned, only RHIC or the LHC are capable of collecting these data, so NASA proposed the project to RHIC.

After the project was presented to RHIC, the STAR (Solenoid Tracker at RHIC) detector volunteered to collect these data. STAR then took NASA's proposal and adjusted it to better suit the properties of the facility, accelerator, and detector. Figure 2 shows the deviation from NASA's plan.

	NASA	STAR
Targets	C, Si-28, Al-27	C, Al-27, Ni-58
Beams	C, Si-28, Fe-56	C, Al-27, Fe-56
Energies	2 – 50 GeV	5, 20, and 50 GeV

Figure 2: A summary of the project proposal from NASA vs. STAR. (Note: the changes from the NASA to STAR proposal are explained in the text.)

STAR replaced the Si-28 target with Al-27 because silicon is fragile and expensive, and an Al-27 target would already be installed for the spacecraft. Due to the properties of the detector, a Ni-58 target was added to act as the Fe-56 beam (Note: Fe-56 could not be used as a target because it is too magnetic; thus, its closest, less-magnetic neighbor was selected). The Ni-58 target data could be Lorentz-boosted as if it were a beam. Finally, the Si-28 beam was replaced with an Al-27 beam since STAR already has an Al-27 beam prepared.

C. Project Overview

STAR justified the changes to NASA's proposal by stating that a difference in one or two nucleons would not cause a statistically significant deviation in the data. NASA wants quantitative proof of this, which was the origin of my project. In other words, the question I sought to answer was: is Ni-58 a valid approximation for Fe-56, and is Al-27 a valid approximation for Si-28?

II. THE GLAUBER MODEL

To answer this question, I used the Glauber Model [2]: a computational model of nucleus-nucleus collisions that allows us to interpret and predict data from particle accelerators. The model starts with the creation of two nuclei, populated according to a Woods-Saxon density. These nuclei are then offset by a randomly generated impact parameter (to replicate an accelerator more accurately). The nuclei are collided one million times, with a new impact parameter being generated for each collision.

Three histograms are constructed from these data: impact parameter (b), number of collisions (NColl), and number of participants (NPart). Examples of each histogram can be found in Figures 3, 4, and 5, respectively.

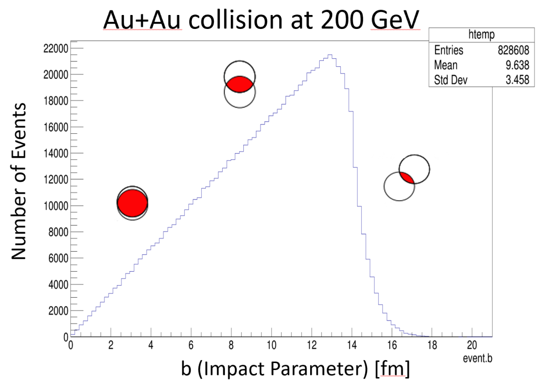

Figure 3: This histogram shows the value of the impact parameter that was randomly chosen for each event. The superimposed nuclei show the impact parameter in red. The linearity of the left-hand side is a result of the linear relationship between the radius and circumference of a circle. The histogram drops off suddenly around 14 fm due to the Woods-Saxon population of the nucleus, which is uniformly distributed until reaching a value close to the radius of the collided element. Finally, the number of events drops to 0 past 16 fm, which is expected as this value is larger than the radius of gold.

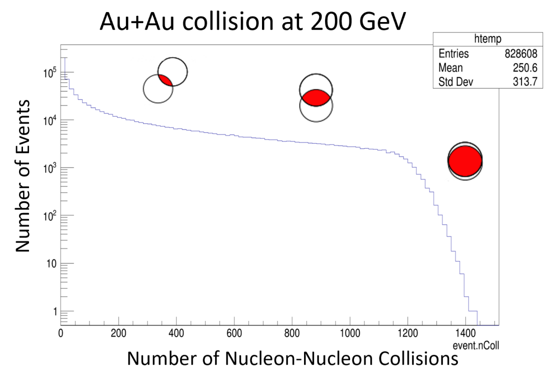

Figure 4: This histogram shows the number of events for a given bin of nucleon-nucleon collisions. The two gold nuclei combined have about 400 nucleons, so it seems incorrect to see up to 1400 collisions in any given event; however, many nucleons collide more than once, resulting in the given distribution. The visual of the impact parameters is again showcased in red to illustrate that more central collisions will yield more nucleon-nucleon collisions.

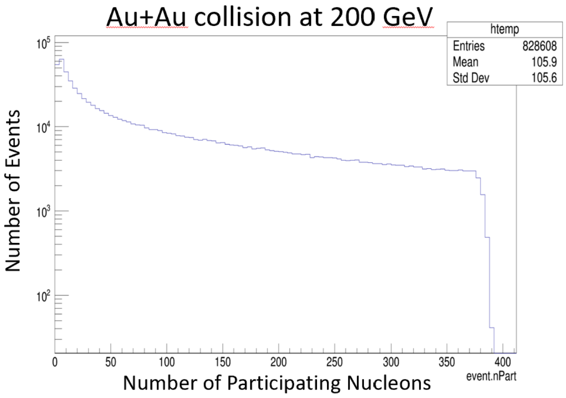

Figure 5: This histogram shows the number of events for a given bin of participating nucleons. A nucleon can have multiple collisions, but whether or not it participates is a boolean (True or False). This results in the maximum number of participants being approximately 400, which is the total number of nucleons in the combined gold nuclei.

After building my Glauber Model, I ran an Au+Au collision at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV and produced Figures 3, 4, and 5 to verify that my model was correct. Once I had a working Glauber Model, I could use it to answer NASA's question: is Ni-58 a valid approximation for Fe-56, and is Al-27 a valid approximation for Si-28?

III. DATA COLLECTION

I used the Glauber Model to model the following collisions Fe+Fe and Fe+Ni then Al+Al and Al+Si (all collisions are at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV). From the NColl plots, I calculated the nuclear cross-section of each collision. The calculation is surprisingly simple.

$$\text{Cross-Section} = \frac{\text{Events}}{\text{Number of Events Ran}} \times \text{Throwing Area}$$

"Events" is the total number of events that had at least one nucleon-nucleon collision. The "Number of Events Ran" is the total number of times the Glauber Model is run in the code. The "Throwing Area" is related to the impact parameter. The code takes x and y bounds for the nucleus collision. For the following histograms, the bounds were set at -15 fm to 15 fm (for x and y). The area is rather arbitrary; however, one must be careful that the area includes the possibility of the two nuclei missing one another (i.e. add the two radii that are being collided and that becomes the minimum upper and lower bound).

I performed the nuclear cross-section calculation for all four histograms (Fe+Fe and Fe+Ni then Al+Al and Al+Si). If the collisions with approximated elements differed by a value of less than five percent from their counterparts (the accepted error of the STAR detector), then it could be declared the approximation was valid.

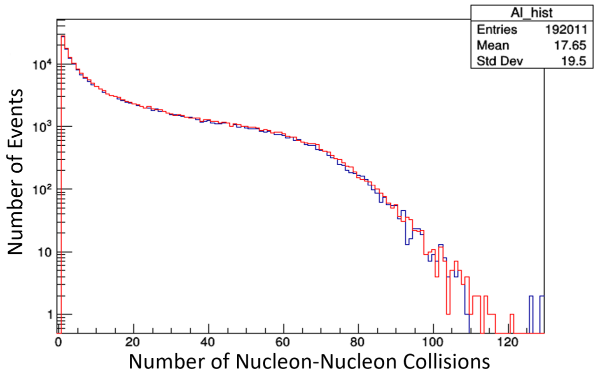

Figure 6: This NColl graph shows the following collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV: Al+Al (red line) and Al+Si (blue line). Qualitatively, it seems Si-28 is a good approximation for Al-27, since the lines almost overlay one another.

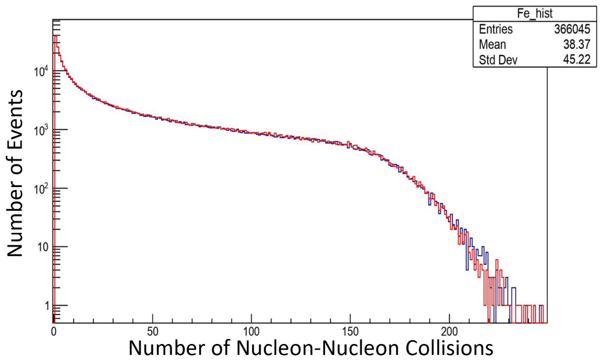

Figure 7: This NColl graph shows the following collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV: Fe+Fe (red line) and Fe+Ni (blue line). Qualitatively, it seems Ni-58 is a good approximation for Fe-56, since the lines almost overlay one another.

IV. RESULTS

The nuclear cross-section (again at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV for all collisions) for Fe+Fe was 2.869 barn, and Fe+Ni was 2.949 barn. This is a difference of 2.7%. The nuclear cross-section for Al+Al is 1.728 barn, and Al+Si was 1.784 barn. This is a difference of 3.2%. As aforementioned, the STAR detector has a 5% error; therefore, our differences in cross-section needed to fall below this value to be accepted. Since the values did indeed fall below this value, I declared the approximation of Si-28 for Al-27 and Ni-58 for Fe-56 to be valid.

V. CONCLUSION

A. Summary

I used the Glauber Model, a computational model of nucleus-nucleus collisions, to answer the question: is Ni-58 a valid approximation for Fe-56, and is Al-27 a valid approximation for Si-28? I ran the Glauber Model for Al+Al, Al+Si, and Fe+Fe, Fe+Ni. From these data, I created NColl histograms, which display the number of nucleon-nucleon collisions. These histograms allowed me to calculate the nuclear cross-section for all four sets of collisions. I found each pair to be within our accepted 5% error bound; therefore, I concluded the approximations to be valid.

B. Next Steps

Now that STAR has these data to present to NASA, the Space Radiation Protection Program will progress to the next stage. The program is tentatively scheduled to run in 2025.

[1] Andrew Davis, *Advanced Composition Explorer (ACE) News*. California Institute of Technology, #83, 2004.

[2] Michael L. Miller et al., *Glauber Modeling in High-Energy Nuclear Collisions*. Annual Review of Nuclear and Particle Science, Volume 57, 2007.