Investigation of the Gamma Radiation Attenuation Properties of $H_2O_{(s)}$,$CO_{2(s)}$, and Martian Regolith

Gamma Busters

“Humanity's interest in the heavens has been universal and enduring. Humans are driven to explore the unknown, discover new worlds, push the boundaries of our scientific and technical limits, and then push further. The intangible desire to explore and challenge the boundaries of what we know and where we have been has provided benefits to our society for centuries.” -Why We Explore, NASA

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Cover Quote: Wiles, Jennifer. "Why We Explore." *NASA*, NASA, 13 June 2013, www.nasa.gov/exploration/whyweexplore/why_we_explore_main.html#.XoMEt9MzYkg.

Introduction

One of the great interests of our time is space exploration. We were inspired by the possibility of a human setting foot on another planet and exploring unknown truths about our universe, and seeing the rising interest in Mars missions from space agencies worldwide, we've decided to propose an experiment related with Mars missions.

One major challenge regarding long-term human missions to Mars is habitation. Mars has no global magnetic field to deflect energetic particles and an atmosphere much thinner than Earth's, so [astronauts will] get only minimal protection from the radiation [1]. In order to shield from these higher-energy particles and their secondary radiation, there are two approaches: Either increasing the sheer bulk of the materials or using more effective shielding materials. The materials that are commonly found on Mars (such as regolith, water ice, and frozen carbon dioxide at poles) can be utilized to increase the sheer bulk of the barrier that protects the astronaut habitats (*Figure 1)*.

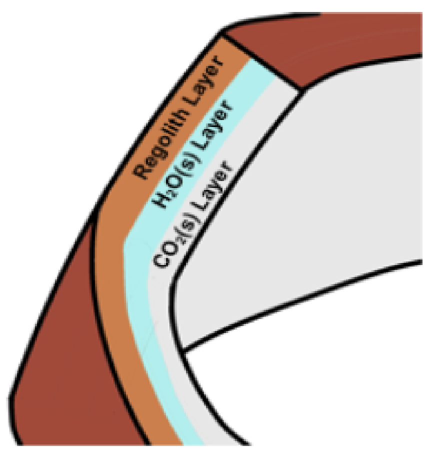

Figure 1 : Additional Protection Layers

During winter at a martian pole, 25–30% of the atmosphere is deposited into slabs of CO_2 ice because of the chilling temperatures due to continuous darkness. After winter, when the poles are exposed to sunlight, the frozen CO_2 sublimes [2]. If covered with regolith, both the frozen CO_2 and H_2O can be captured for shielding, with no effort required to deposit CO_2 on the habitat walls. For these reasons, we want to test how effective these materials are at attenuating harmful energetic particles. We focused on gamma photons because gamma radiation is both very penetrating and abundant on the surface of Mars (*Figure 2*). We will recreate gamma radiation ranges found on Mars by using bremsstrahlung photons.

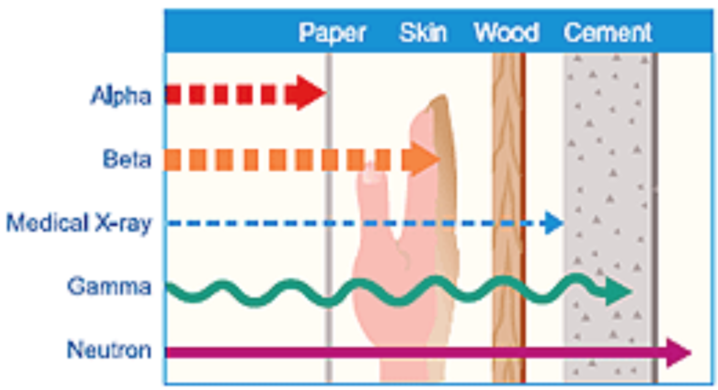

Figure 2: Penetration Ability of Various Radiation Types

(printed from "Radiation Types." U.S. NRC https://www.nrc.gov/about-nrc/radiation/health-effects/radiation-basics.html [3])

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Our research question is "How does the thickness of $H_2O_{(s)}$ / $CO_{2(s)}$ / Regolith affect the amount of gamma radiation up to 300MeV that is attenuated?"

Theoretical Background

When gamma rays interact with matter, various physical phenomena occur that alter the path and the amount of energy carried by the photons. The main ones are Photoelectric Effect, Compton Scattering, and Electron-Positron Pair production. These interactions become dominant between certain energy ranges for each material *(Figure 3)*. Since our beam will be polyenergetic, different effects will be dominant depending on the beam composition.

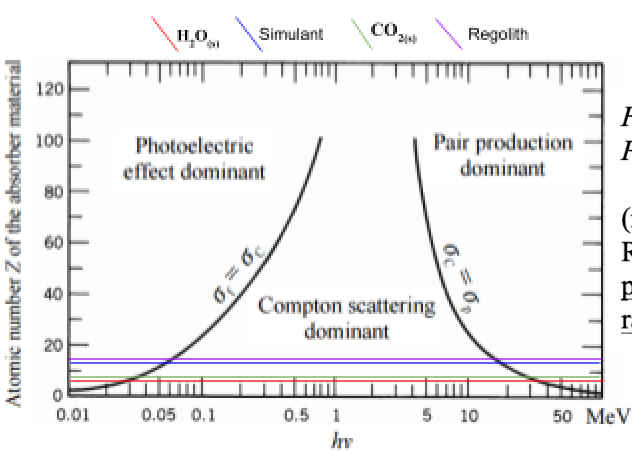

Figure 3: Effective Atomic Number Versus Energy of the Photon

(modified with permission from "Interaction of Gamma Radiation with Matter." *Nuclear Power*, www.nuclear-power.net/nuclear-power/reactor-physics/interaction-radiation-matter/interaction-gamma-radiation-matter/.[4])

Photoelectric Effect

The gamma photon’s total energy is absorbed by an electron which is ejected from the atom as seen in *Figure 4*. The photoelectric effect is more frequent in substances with a higher electron density. [5]

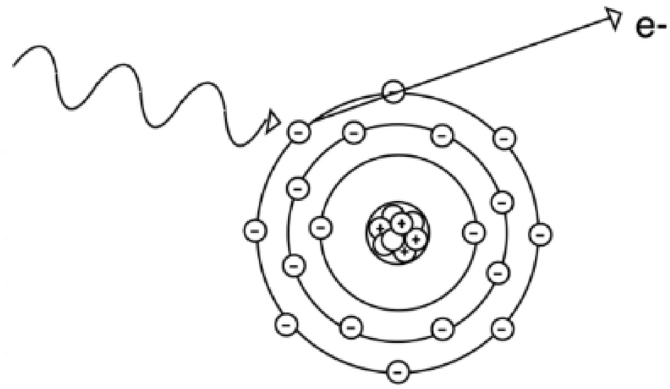

Figure 4: Photoelectric Effect
(Modified with permission from John Vagabond [6])

Compton Scattering

Some of the gamma photon’s energy is absorbed by an electron which is ejected from the atom as seen in *Figure 5*. Both the electron and gamma photon are scattered from the atom with an angle. [7]

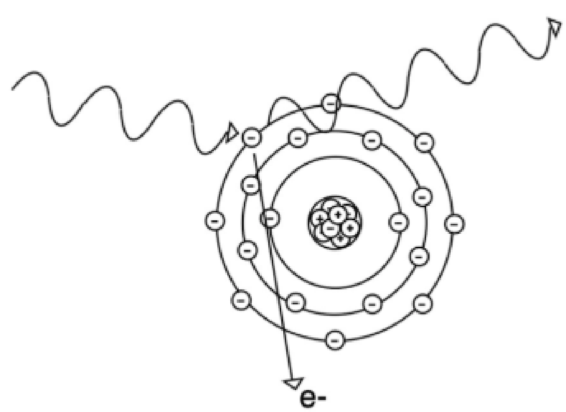

Figure 5: Compton Scattering
(Modified with permission from John Vagabond [6])

Pair Production

This effect occurs when the gamma photons are absorbed in the Coulomb field of the nucleus and annihilated to create an electron-positron pair as seen in *Figure 6*. In pair production, the energy from the gamma photon is completely absorbed. [8]

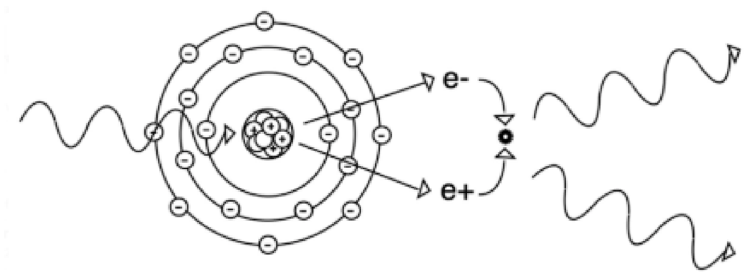

Figure 6: Pair Production
(Modified with permission from John Vagabond [6])

Experimental Setup

The gamma photon energy range on the surface of Mars was measured to be around 0-300MeV by the Radiation Assessment Detector (*Figure 7*). Therefore in our experiment, we will need to produce Bremsstrahlung photons in that range. To achieve these low energy bremsstrahlung photons, a tertiary target will be put inside the testing area. The collimated beam of electrons will hit that target and produce bremsstrahlung photons between 0-300MeV.

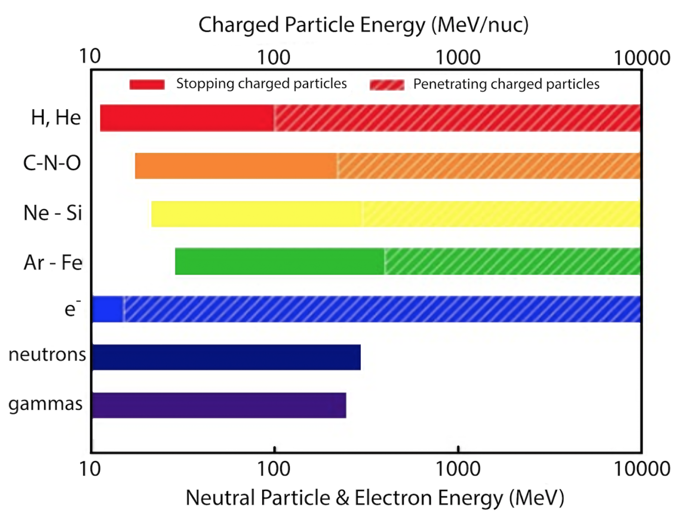

Figure 7: Various radiation types and energies detected by RAD on Mars.

(printed from Hassler, D. M., et al. "Space Weather on the Surface of Mars: Impact of the September 2017 Events." AGU Journals, John Wiley & Sons, Ltd, 7 Nov. 2018, agupubs.onlinelibrary.wiley.com/doi/10.1029/2018SW001959[9])

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While we were researching the DESY 2 beam facility, we found a bremsstrahlung momentum distribution for a 6.3GeV/c electron beam hitting the primary target at the synchrotron (*Figure 8*).

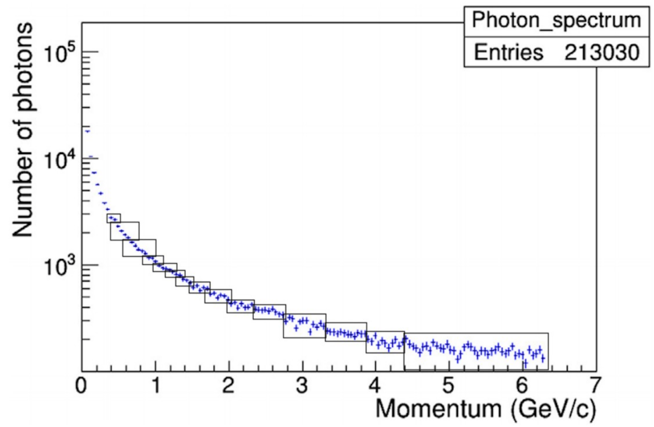

Figure 8: Number of Photons versus Momentum of the Photons for a 6.3GeV/c electron beam hitting the primary target

(printed with permission of Dr. Paul Schütze from "The DESY II test beam facility" https://doi.org/10.1016/j.nima.2018.11.133, NIMA, Volume 922, 1 April 2019, Pages 265-286. [10])

The number of total bremsstrahlung photons[1] was determined from the graph to find the point where the cumulative percentage equals 90%. The electron beam momentum that would make the 90% of bremsstrahlung photon momenta between 0-0.3GeV/c [2] was found as 0.6GeV/c [3]. (*Figure 9*)

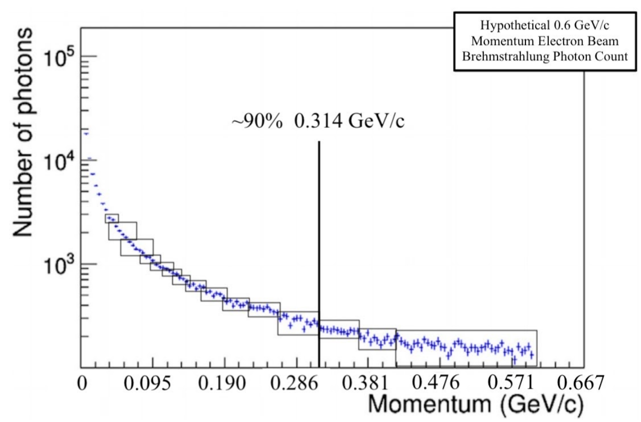

Figure 9: Number of Photons versus Momentum of the Photons for a Hypothetical 0.6GeV/c electron beam hitting the primary target

(modified with permission of Dr. Paul Schütze from "The DESY II test beam facility" https://doi.org/10.1016/j.nima.2018.11.133, NIMA, Volume 922, 1 April 2019, Pages 265-286. [10])

[1] The average of the data points were taken and multiplied by the number of the data points to determine the number of photons inside the rectangles.

[2] Different initial electron beam momenta could be chosen to get different percentage distributions for specific momenta. For example, a beam may be adjusted so that the most frequent momentum is 0.2GeV/c

[3] The bremsstrahlung momentum distribution would follow the same pattern regardless of the initial electron beam momentum because the bremsstrahlung momentum is inversely proportional to the momentum of the initial electron beam.

For monoenergetic beams of photons, there is an attenuation coefficient formula. However, for our polyenergetic beam, which is a more realistic description of radiation on the Martian surface, we want to find out the HVL[4] and TVL[5] of $H_2O_{(s)}$ / $CO_{2(s)}$ / Regolith.

We will use MGS-1 Mars Global simulant as the martian regolith target. (MGS-1 Mars Global simulant has an effective atomic number of 14.05 while Regolith has 14.55; therefore, there's a deviation of 3.42%) Our other targets are $H_2O_{(s)}$ and $CO_{2(s)}$ (*Figure 10*).

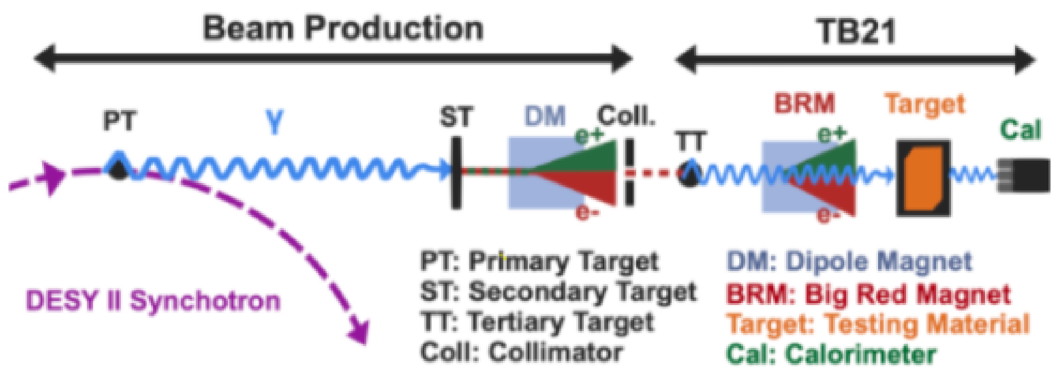

Figure 10: The Setup of the Experiment

Procedure

1. The electron-positron pairs arriving from the secondary target are adjusted with the dipole magnet and the collimator so that only the electrons with the momentum of 0.6GeV/c are allowed to pass.
2. In the experimental area, a tertiary target[6] will be placed to produce bremsstrahlung photons with a specific momentum distribution when collided with the electrons coming from the collimator.

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[4] Half Value Layer: the thickness of a material at which 50% of the incident energy has been attenuated
[5] Tenth Value Layer: the thickness of a material at which 90% of the incident energy has been attenuated
[6] The tertiary target will function the same as the primary target in the way that it will contain carbon fibers that produce bremsstrahlung photons when electrons collide with it.

3. After bremsstrahlung photons are produced, the big red magnet (BRM) will get rid of the unwanted charged particles, and the photon beam will collide with our sample.

4. The energy of the attenuated photons coming out of our sample will be detected by the lead calorimeter[7].

Limitations

- One of the limitations is using a simulant to test attenuation characteristics of martian regolith. As mentioned before, their effective atomic masses differ by 3.42%.

- We can only determine the total amount of energy that manages to pass the samples which prevents us from deducing at which momenta the photons were attenuated the most.

- We will only be sending gamma photons on our targets from a single angle, whereas in Mars, the targets will be exposed to the radiation from many angles.

- Scattering of gamma photons in the medium before reaching the detector will reduce the accuracy.

[7] A scintillator for a more precise measurement can be used. However when we researched about NaI(Th) scintillators, we learned that they become very inefficient at the energy levels we are planning to measure (0-300 MeV). If there is another type of scintillator that could withstand our energy intervals, we could try that as well.

What We Hope to Take Away

- We want to investigate the attenuation properties of martian regolith, $H_2O_{(s)}$, and $CO_{2(s)}$ when encountered with a polyenergetic gamma beam. This would enable us to propose an applicable solution to minimize the radiation exposure of astronauts on Mars.
- Each team member will record a vlog about our journey, which will later be combined and uploaded to youtube, to allow people to see the experiment from different perspectives, hopefully inspiring others to undertake science projects. We believe that our experiment will increase the interest in particle physics and space exploration in our age group. This may hopefully lead to increased funding to scientific research and scholarships, especially in particle physics-based projects in Turkey, in the future.
- Most of our group members want to study physics at university. Being able to delve into the research world this early would be a unique opportunity for us.

Acknowledgements

We would like to thank,

Our physics teacher Hüseyin Köse for guiding us to the right sources which allowed us to deepen our research, and his continuous feedback on our ideas and our report along the course of the creation of the project.

Dr. Paul Schütze for kindly answering our questions about the specifications of the equipments at the DESY II facility and letting us use the graphs in one of his articles.

The founder and CEO of XArc Exploration Architecture Corporation, Sam Ximenes, for his kind effort to send the newest illustration of mars habitation for us to use on the cover page.

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Appendix

Chemical Composition of Martian Regolith	
Oxides and Elements	**Percentage%**
SiO_2	46.52
TiO_2	0.87
Al_2O_3	10.47
Cr_2O_3	0.36
Fe_2O_3	4.20
MnO	0.33
MgO	8.93
CaO	6.27
Na_2O	3.02
K_2O	0.41
P_2O_5	0.83
SO_3	4.90
FeO	12.18
Cl	0.6100
Ni	0.0544
Zn	0.0204
Br	0.0049
Total Percentage	**99.98**

(printed from Ming, Douglas W., and Richard V. Morris. "CHEMICAL, MINERALOGICAL, AND PHYSICAL PROPERTIES OF MARTIAN DUST AND SOIL." 13 June 2017. [11])
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MGS-1 Mars Global Simulant Composition	
Oxide	**Percentage %**
SiO_2	45.57
TiO_2	0.30
Al_2O_3	9.43
Cr_2O_3	0.12
Fe_2O_3T	16.85
MnO	0.10
MgO	16.50
CaO	4.03
Na_2O	3.66
K_2O	0.43
P_2O_5	0.37
SO_3	2.63
Total Percentage	99.99

(printed from "Planetary Simulant Database: MGS-1 Mars Global Simulant." Center for Lunar Asteroid Surface Science, sciences.ucf.edu/class/simulant_marsglobal/.[12])
(The mineral recipe and production methods are available for anyone to reproduce and modify MGS-1 based simulants as they see fit.)

In order to calculate the effective atomic number of the regolith and simulant we developed a software that calculates the effective atomic number, percentage uncertainty and shows several graphs. The code can be found in this link.