Examination the cosmic ray muon attenuation by heavy metal alloys

Rasha N. I. Altameemi¹, Nurul Shazana Abdul Hamid¹* and Wan Mohd Aimran Wan Mohd Kamil¹

¹Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia.
*Corresponding author: shazana.ukm@gmail.com

Abstract. The ability of a muon telescope to detect high dense metal elements was experimentally determined in previous works. Recently, the muon absorption has become one of the most important data in the tomography technique. In the present study, the absorption coefficients of muon at ground level for heavy alloys, namely brass, steel and stainless steel have been successfully recorded. The experiment was performed in Bangi, Malaysia with coordinates of 101.78° E, 2.92° N and elevation of 30 m above sea level. Muon examination was made by muon telescopes contained of two Geiger-Muller detectors. The muon count rate graphs showed an initial increase, followed by a transition depth and then a decrease with the continuous increase of the alloys thickness. The transition points observed were reliable and consistent with the properties of the alloys. The absorption coefficient of brass was higher than the other alloys; therefore, brass could be detected by cosmic ray muons easily. The results confirmed that the larger the mass density of the alloy absorber, the higher the ability to absorb the muon. The attenuation stated by this experiment would be valuable for coming work on muon revealing procedures.

1. Introduction

The primary cosmic ray is a high energy radiation that originates from the Solar System in outer space. Upon impact with the Earth’s atmosphere, it primarily collides with the molecules from the atmosphere with a typical rate of 104 particles /m²-min and eventually decays into secondary particles which include muons, positrons, pions and neutrons [1]. Notably, the muon is the easiest detectable elementary particle with an electrical charge of -1 e on the earth’s surface. It is also known as a heavy electron and behaves as an energetic penetrating particle which is capable of passing through dense and thick matter on the Earth’s surface at various angles ranging from the vertical to the horizontal [2]. This occurrence is due to its greater mass that halts the bremsstrahlung effect and prevents high energy loss [3]. The unique nature of muons has resulted in it being selected as a primary source used in radiographic imaging for large and dense objects in order to overcome the limitations of conventional radiography [4]. Cosmic ray muons can be used to determine heavy matters such as metals in muography [5].

Cosmic-Ray Muon undergoes an electromagnetic cascade when interacting with a thick absorber/matter, resulting in a secondary high energy particle (e+, e−, γ). There are two main processes involved, namely pair production and bremsstrahlung effect [6]. However, the bremsstrahlung occurs...
less in muon decay as a result of its high mass and constituted energy. For example, an incoming muon would intensely interact with atoms existing in the material via weak interaction and subsequently decays to new secondary particles with lower energy. Therefore, it is supposed that numerous of interactions happen impulsively until all their energy will vanish and the particles will absorb [7].

Muon tomography is a technique based on muon flux attenuation, where images are produced by focusing on the angular distribution of the attenuation. Previously, detection of mostly metal-based medium and light materials as contraband using muon tomography was experimentally studied. The concept of attenuation-based tomography has been proven to be feasible as results from GEANT simulations showed that electrons produced by muons interact well with light materials and can form the basis of how such materials may be discerned [8]. However, a study on the diffusion of muons in shielding materials using Monte-Carlo techniques showed that solving the complex problem of muon shielding materials requires sophisticated software [9]. Recently, a portable telescope comprising two detectors with sufficient efficiencies for measuring count rate of muons at sea level was designed for the purpose of studying variations of muon intensity with the zenithal and azimuthal angles [10]. In this report, we aim to measure the attenuation coefficients of heavy materials such as alloys and replace the gap in scientific knowledge left unexplored by previous studies.

In this study, the muon telescope was used to examine the absorption coefficients of heavy alloys (brass, steel and stainless steel). The intensity of the muon flux spread inside the dense alloys with different depths were obtained and the fitting was applied to calculate the muon attenuation factors. The determination of the muon attenuation factors of the dense matters involve simple and portable telescope could be made more consistent for future researches and this is our goal in the present report.

2. Muon attenuation

It is worth mentioning that the muon count rates depend on the shielding material thickness. This claim can be observed from the different trend of Rossi Curve as measured in varied thickness of shielding material [11]. From the Rossi-Curve, the transition point and the absorption (attenuation) coefficient ($\mu$) for the respective metal sheets can be determined. Generally, there is three important regions in Rossi Curve which is (i) increasing path, (ii) transition depth, and (iii) decreasing path. The increasing region consists of the information related to electromagnetic cascade particles [12]. The transition point is a point to transit from increase to decrease path. Meanwhile, the decreasing region comprise the details of the exponential decay of a muon when penetrated through a matter substance (particle absorption) and can be related to the following equation:

$$ R = R_0 e^{-\mu x} \quad (1) $$

where $R$ is the muon count rate, $R_0$ is the initial count rate i.e. when there is no shielding, $\mu$ is the attenuation coefficient, $x$ is the shielding material thicknesses, when $R$ and $x$ have been measured, the absorption coefficient can be determined from the slope obtained after fitting,

$$ \ln (R) = \ln (R_0) - \mu x \quad (2) $$

Eq. (2), involved in the current report, is represent a classical technique to determine the attenuation coefficient experimentally.

3. Methodology

The focus in this framework involves measuring the count rates of muons that penetrate different alloys i.e. brass, steel and stainless-steel plates of varying thicknesses. Experiments were performed inside the
laboratory in the Department of Applied Physics at University Kebangaan Malaysia, located at 101.78° E, 2.92° N, 30 m above sea level. The telescope was designed from two gaseous detectors (GM counters), which are chosen for muon detection due to their sensitivity in detecting intensities of these charged particles [13,14]. Furthermore, the effectiveness of this telescope has been validated by both experimental and statistical approaches [15]. Investigations on the attenuation coefficient of high-density elements was also carried out using these telescopes as well [16]; Therefore, the efficiency of this design for measurements in determining absorption (attenuation) coefficients of detectable high-density alloys is well established. Thicknesses of the 20 cm × 20 cm alloy sheets used in this experiment are presented in Table 1. Numerical values for the count rate was recorded across a time period of 24 hours after insertion of the absorber and is repeated for all variation of parameters in the samples as listed in Table 1.

| Table 1. Alloys sheets thicknesses. |
|------------------------------------|
| Metal                              | Single sheet/slide thickness | Total thickness (cm) |
| Brass                              | 35 sheets of 0.2 cm each     | 7                   |
| Stainless Steel                    | 90 sheets of 0.2 cm each     | 18                  |
| Steel                              | 90 sheets of 0.2 cm each     | 18                  |

4. Results and discussions

Relationship between muon count rate as measured by the muon telescopes and thickness, \( x \) of the brass absorber used is represented in Figure 1 (a). Rapid growth is expected and continues until it reaches a maximum known as the transition point, after which the count rate starts decaying exponentially. The underlying principle beneath the observed decay has been widely accepted as an effect exhibited by the exponential attenuation of muon flux intensity in shielding materials. It was also established that attenuation coefficients for different shielding materials varied with material densities [11,17]. The trends obtained from the graphs for the brass absorbers served to validate the effectiveness of the set-up telescope in achieving the objectives.

![Figure 1.](image_url)
Based on Figure 1 (a), the transition point is estimated to occur around 2.75 cm. This value was obtained by performing curve fitting on the obtained data. Such agreement confirms not only the capability of the set up to measure fluctuations in muon count rate, but also its effectiveness in determination of attenuation coefficients for heavy materials. Combining Eq. (2) and data extracted from as-performed least squares curve-fitting, attenuation coefficient of the used brass alloy was depicted as a slope in Figure 1 (b) with a value of $(0.13 \pm 0.02) \text{ cm}^{-1}$. Similar measurement and analysis procedures were also conducted to determine the attenuation coefficient of other alloys, namely steel and stainless steel and the obtained results are represented in Figure 2 and Figure 3. The count rate-specimen thickness graphs of the other alloys also displayed distinct behaviors with transition points of at approximately 3.2 cm and 4.2 cm for stainless steel and steel respectively. Transition depth is said to be an alloy-specific property, similar to ability of different metals in absorbing cosmic muon. In short, muon absorption ability of a metal depends on the mass density and the atomic number of that particular metal.

From Table 2, it is evident that transition depth decreased when the density of the absorber increased. The higher the mass density of the alloy, the higher the capability of absorption. Many of the earlier studies examined the variation of muon count rate in relation to penetration depth; however, the
attenuation coefficients for different alloys remain undefined. Recently, the attenuation coefficient of steel was determined experimentally to be around 0.125 cm$^{-1}$. On the other hand, theoretically calculations carried out using the simulation program GEANT yielded the attenuation coefficient to be approximately 0.03 cm$^{-1}$ [7]. This difference can be attributed to a multitude of factors including energy dependence, experimental setup and position where the measurements are taken. The larger value of attenuation coefficient for brass (see Table 2) indicates that distinction between heavy alloys and lighter ones via muon absorption is feasible. The obtained coefficients for the alloys will have important implications in the field of attenuation in the future.

Table 2. The attenuation coefficient values measured from the decreasing region at ground level cosmic ray muon using different alloys sheets.

| M          | ρ (g/cm$^3$) | Transition depth (cm) | µ ± Δµ ( cm$^{-1}$) |
|------------|-------------|-----------------------|---------------------|
| Brass      | 8.73        | 2.75                  | 0.13 ± 0.02         |
| Stainless steel | 8.00    | 3.20                  | 0.09 ± 0.01         |
| Steel      | 7.70        | 4.20                  | 0.08 ± 0.01         |

The Table 2 parameters are, ρ is the density of the alloys sheets, the transition point of the alloys as shown in the Figures (1a-3a), µ is the absorption coefficient represent by the slope of the straight lines from the Figures (1b-3b) and Δµ is the standard error of the slope.

5. Conclusion

As steel has lower density compared to the other alloys in this experiment, it is the preferred shield against beta radiation since cosmic muons have a higher degree of similarity to gamma rays and can only be shielded by heavier alloys like brass. This characteristic of alloy in relation to cosmic muon absorption validates the prospect of using muon telescopes as tools for alloy detection since they have very large attenuation coefficient. Not only that, detection could potentially be extended to a larger range of materials since results suggest a correlation between density and muon absorption capability in a material. In this aspect, transition depth acts as an excellent reference as beyond this point attenuation occurs, thus enabling detection.

Acknowledgment

We would like to acknowledge the Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia (UKM) for permitting the use of their laboratory space to conduct our observations. We also acknowledge grant GP-2019-K018967 provided by UKM.

References

[1] Gaisser T K and Stanev T 2004 The review of particle properties Phys lett. B 592, 228 – 234
[2] Hanna D 2012 Early muon-physics measurements with cosmic rays Physics in Canada 68,7 –11
[3] Mollerach S and Roulet E 2018 Progress in high-energy cosmic ray physics Progress in Particle and Nuclear Physics, 98, 85–118
[4] Morris C L, King N S P, Kwiatkowski K, Mariam F G, Merrill F E and Saunders A 2013 Charged
particle radiography Reports on Progress in Physics 76(4)

[5] Bonal N D, IV A T C, Cieslewski G, Dorsey D J, Dreesen W, Foris A, Green J A, Miller T J, Preston L A, Roberts B L, Schwellenbach D and Su J C 2016 Using muons to image the subsurface Sandia Report pp. 1-64.

[6] Apel W D, Arteaga-Velázquez J C, Beka K, Bertaina M, Blümer J, Bozdog H, Brancus I M, Cantoni E, Chiavassa A, Cossavella F, Daumiller K, DeSouza V, DiPierro F, Doll P, Engel R, Fuhrmann D, Gherghel-Lascu A and Zabierowski J 2017 Probing the evolution of the EAS muon content in the atmosphere with KASCADE-Grande Astroparticle Physics vol. 95, 25–43

[7] Schreiner III H F 2016 Methods and simulations of muon tomography and reconstruction Retrieved from http://hdl.handle.net/2152/39757

[8] Blanpied G, Kumar S, Dorroh D, Morgan C, Blanpied I, Sossong M, McKenney S and Nelson B 2015 Material discrimination using scattering and stopping of cosmic ray muons and electrons: Differentiating heavier from lighter metals as well as low-atomic weight materials Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 784, 352–358.

[9] Stevenson G R 1986 Shielding of muons Internal IAEA report TIS-RP-IR-86-05

[10] Autran J L, Munteanu D, Saoud T S and Moindjie S 2018 Characterization of atmospheric muons at sea level using a cosmic ray telescope Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 903, 77-84, Jun

[11] Jánossy L and Nagy L 1957 Experiments on the Rossi curve Acta Physica Academiae Scientiarum Hungaricae 6(3): 467

[12] Altameemi R N I, Hamid N S A, Mohd W M A W K and Ahmed S M S 2020 Phenomenological cosmic-ray muon attenuation coefficients of Pb, Cu, Zn and Al Submitted to Journal of Radiation Research and Applied Sciences TRRA-2019-0223

[13] Procureur S 2017 Muon imaging: Principles, technologies and applications Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 878, 169–179

[14] Altameemi R N I and Gopir G 2016 Effect of copper and aluminium on the event rate of cosmic ray muons at ground level in Bangi, Malaysia AIP Conference Proceedings 040005

[15] Altameemi R N I, Hamid N S A, Mohd W M A W K, Ahmed S M S and Gopir G 2019 Investigation of simple portable telescope validity for muon detection inside metals Sains Malaysiana 48, 377–383

[16] Altameemi R N I, Hamid N S A, Mohd W M A W K and Ahmed S M S 2019 Determination of muon absorption coefficients in heavy metal elements Journal of Radiation Research and Applied Sciences 12:1, 281-288

[17] Nagy L 1958 Shower production at small thicknesses of absorber Acta Physica Academiae Scientiarum Hungaricae 9(1): 63 –72