A Laboratory Study of Cosmic Ray Produced Radionuclides with Muons

JOSEPH L. BREEDEN
Martinsville High School
Martinsville, Indiana 46151

Muons are a major constituent of the secondary cosmic radiation detected at sea level. They comprise 63% of the secondary radiation while 21% are neutrons, 15% are electrons, and <1% are pions and protons. This secondary cosmic radiation is responsible for 30 - 40% of the total natural background radiation (NCRP Report No. 45).

Electrons, taus, and their respective neutrinos and antiparticles are members of the family of leptons along with the muon. Leptons are particles which interact exclusively through weak and electromagnetic forces. The muon possesses a mass of 105.7 MeV/c^2, charge of ± 1, and a spin of ½. It is simply a more massive version of the electron.

Both positive and negative muons are produced in the atmosphere via the decays: $\pi + \rightarrow \mu + + \nu_\mu$ and $\pi - \rightarrow \mu - + \bar{\nu}_\mu$.
These muons can then free decay by the processes:

$$\mu + \rightarrow e + + \nu e + \bar{\nu}\mu \text{ and } \mu - \rightarrow e - + \bar{\nu} e + \nu\mu.$$

The negative muons also can decay via a capture decay: $\mu- + p \rightarrow n + \nu_\mu$ with the proton being bound in the nucleus of an atom. In the capture decay, the muon first enters an orbit around the nucleus. It then falls rapidly (10^{-13} sec.) into the nucleus and interacts with a proton forming a neutron and a neutrino thus changing atomic number of the element. Muon decay differs from that of electron capture because the muon capture process deposits an average of 35 MeV to the residual nucleus and is thus capable of ejecting several neutrons from the atomic nucleus. Therefore, the atomic mass can be changed through muon capture decay as well as the atomic number. The rate at which this occurs is dependent upon the Z or atomic number of the element.

The process of greatest interest here is the muon capture decay. It was the intent of this experiment to obtain data through radiochemical analysis of muon interaction products. Information such as this is vital to more fully understanding interactions mediated by the weak force.

One approach at acquiring this data is to use a scintillation detector with appropriate electronics to mesure Δt, the time interval between the muon entering the detector and the muon decay. This detector is a new type employing a plastic box filled with water and coupled to a photomultiplier tube. The water has proven to be as good, if not better, as a scintillator compared to more expensive systems. Since water is almost a universal solvent, a chemical solution may be placed in the box allowing for great experimental flexibility at a low cost. A chemical of the desired Z was dissolved therein. This study yields new information on the muon capture decay lifetime in various elements.

For the scintillation detector, a simple electronics system was employed. As a muon enters, it emits Cêrenkov radiation which is picked up by a photomultiplier as a start signal. Shortly thereafter, a stop signal follows from the muon decay. These signals go through a Timing Filter Amplifier, a Constant Fraction Discriminator, a Time to Pulse Height Converter, and then into a Multichannel Analyzer. The data was graphed in the form of counts vs. Δt (Figure 1). The results of the present study show an average lifetime of 2.27 ± 0.17 μs

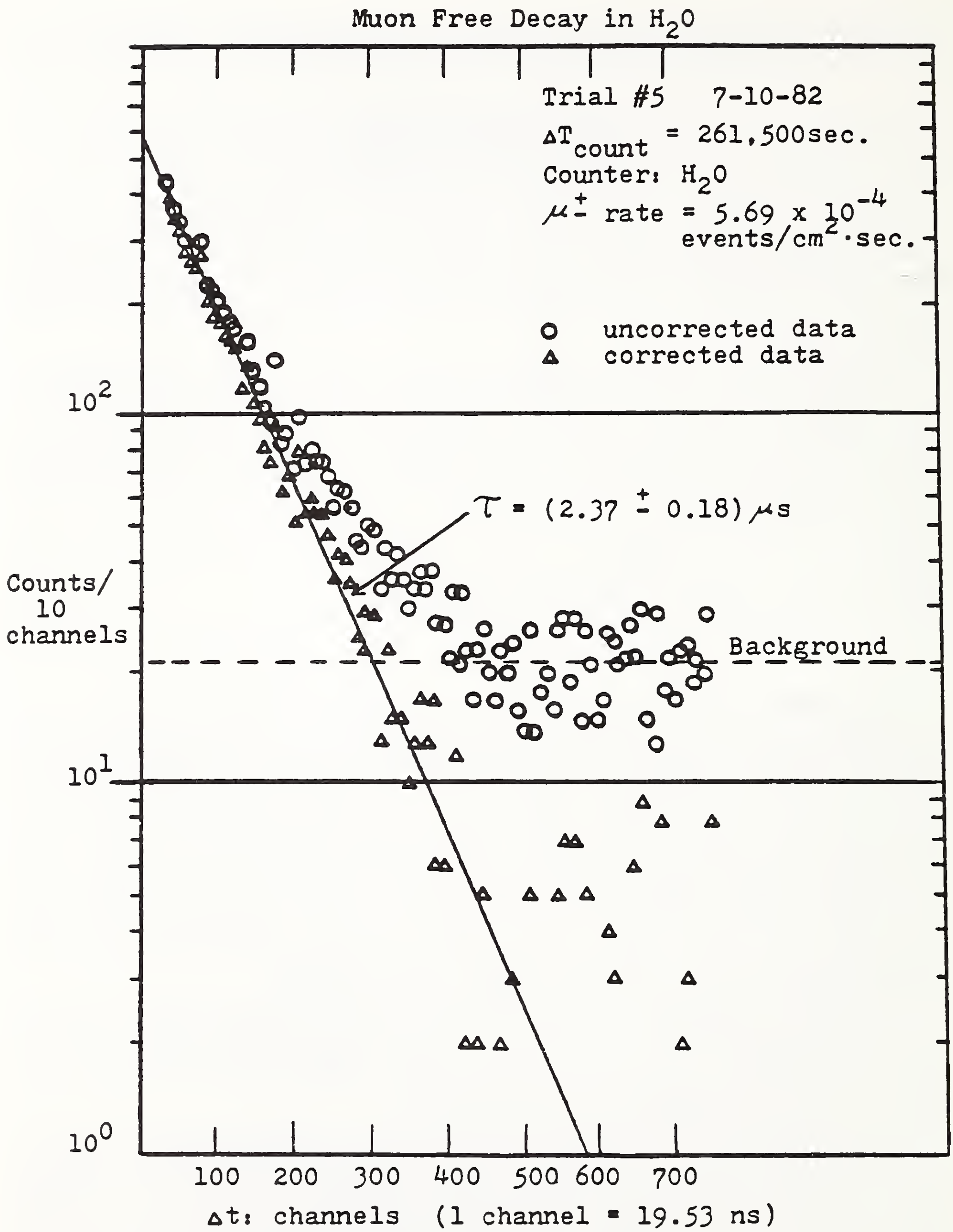

FIGURE 1

which is to be compared with the accepted free lifetime value of 2.19712 ± 0.000077 μs (Table 1), (Reviews of Modern Physics, 1980).

A second approach is to measure the rate of muon induced radioisotope production through a radiochemical analysis. The desired chemical was dissolved into a large volume of water, approximately 50-100 L to accommodate the low cosmic ray muon flux. Cadmium nitrate was used in order to produce Ag isotopes. Then $AgNO_3$ and HC1 were added providing AgCl precipitate which was then filtered out. Rainwater was alternatively used since the $\sim$1% concentration of

TABLE 1. *Muon Free Decay in H_2O Scintillation Detector*

Trial #	Total Events	Mean Lifetime	Counts/cm^2.sec.
3	2327	2.10 ± 0.07 μs	5.809×10^{-4}
4	1383	2.34 ± 0.44 μs	3.684×10^{-4}
5	6954	2.37 ± 0.09 μs	5.688×10^{-4}

argon in the atmosphere yields chlorine isotopes upon μ- capture. The same chemical procedure was then followed. The gamma rays produced from the decay of the isotopes were then measured. In this manner, the distribution of the muon capture products could be measured.

In the large volume radiochemical analysis, entering muons preferrentially seek out the element of highest Z, due to charge transfer processes, and capture upon it. By utilizing a $Cd(NO_3)_2$ solution it is expected that ^{111}Ag, ^{112}Ag, ^{113}Ag, and ^{115}Ag are isotopes produced which can be detected using a standard Ge(Li) gamma ray detector. An energetic muon capture should release excess energy thus knocking neutrons out of the residual nucleus and allowing for the various silver isotopes. The distinctive gamma ray peaks of these isotopes were as follows: ^{111}Ag at 342 keV, ^{112}Ag at 617 keV, ^{113}Ag at 298 keV, and ^{115}Ag at 230 keV. Preliminary analysis has yielded negligible results due to high background and low count rates. Further experiments will be carried out in order to reduce the background and obtain a definite signal.

When using rainwater as a source of a sample, atmospheric Ar is converted into ^{34}Cl, ^{38}Cl, ^{39}Cl, ^{40}Cl as a result of the capture decay with subsequent neutron emission. The gamma ray peaks of these radionuclides are: ^{34}Cl at 146 and 2127 keV; ^{38}Cl at 1642 and 2168 keV; ^{39}Cl at 250.3, 1267, and 1517.4 keV; and ^{40}Cl at 1461 keV. Results of the rainwater study for the production of ^{39}Cl were plotted and compared with a previous study (Figure 2), (Young, et al., 1968). The first trial was a rainfall with a rate of 1.25 in./hr. which yielded 5 dpm/L. The second sample was obtained from a low rainfall rate of 0.025 in./hr. and yielded 70 dpm/L. These findings are in good agreement with Young, et. al. and indicate the general nature of rain formation from water vapor condensation on aerosol particles in the atmosphere. Young, et. al. have determined that the radionuclide concentration present in the aerosol particle depends upon the size of the raindrop formed. Therefore, the smaller the raindrop, the larger the dpm/L and the lower the rainfall rate. The log normal concentration of activity vs. the rainfall rate is simply inversely proportional to the rainfall rate or the size of the raindrops (Figure 2).

This project is part of a continuing study of muon interactions investigating the bound state quark structure of the nucleus. The cosmic ray muon data obtained from the scintillator measurements exhibit a suitable degree of accuracy at a greatly reduced expense. As a result of this study, an interesting discovery was made pertaining to the concentration of radioisotopes and the size of a raindrop. This may prove to be a valuable source of information concerning aerosol particle formation.

I wish to acknowledge the research advice and encouragement of Dr. Thomas Ward of IUCF and Mr. Walter Cory of the High School Science Student Institute. This work was performed under the auspices of the National Science Foundation.

Literature Cited

1. Natural Background Radiation in the U.S. 1975. Report #45. National Council of Radiation Protection: Washington, D.C. p. 12

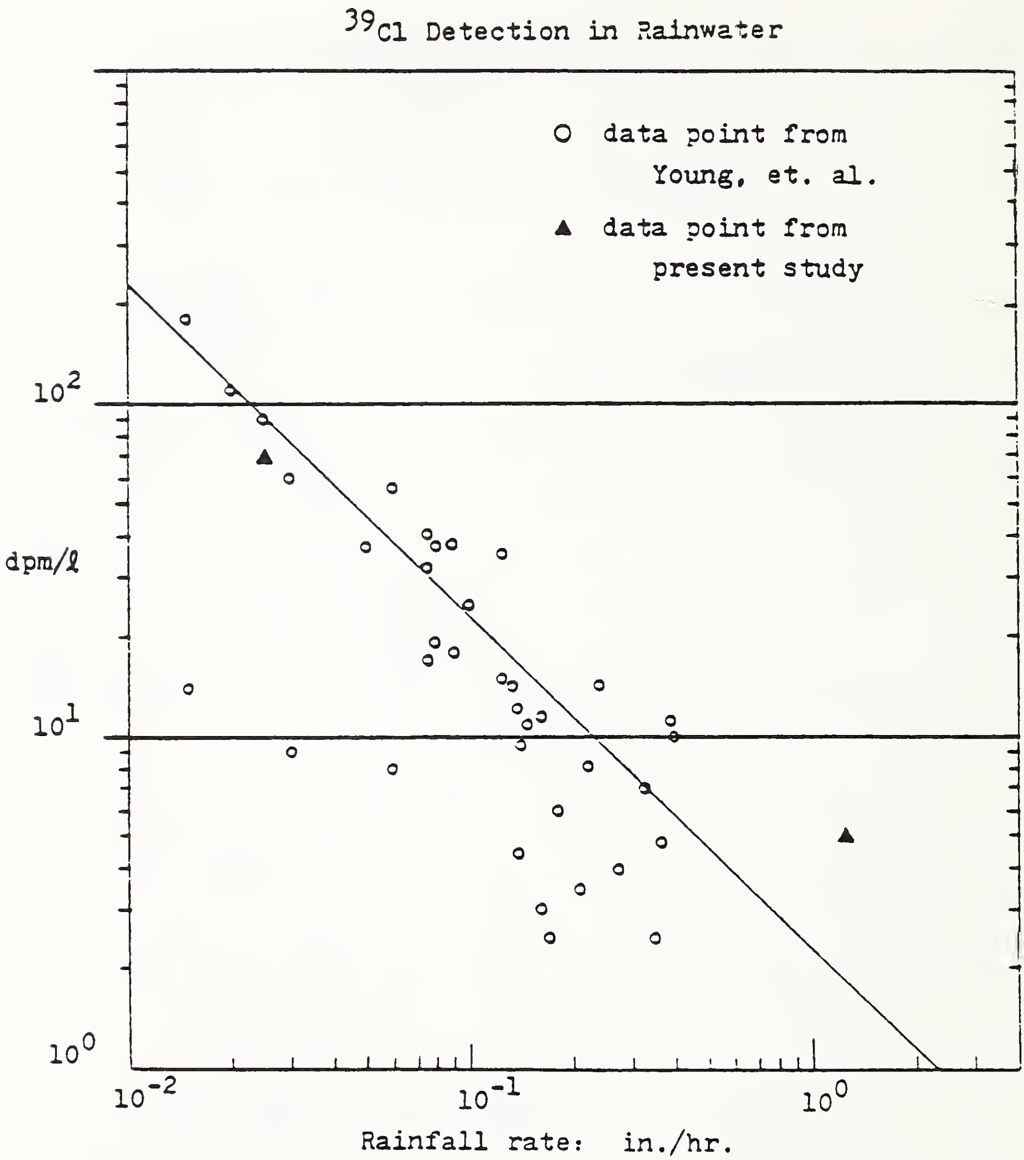

FIGURE 2

2. Review of Particle Properties. April, 1980. Reviews of Modern Physics 52 (2): p. 517.
3. YOUNG, et. al. 1968. Short Lived Cosmic Ray Produced Radionuclides as Tracers of Atmospheric Processes. Radionuclides in the Environment: pp. 513-520.