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LAB REPORT 2: Cosmic and Terrestrial Ionizing Radiation

ABSTRACT

In this lab report, I explore the spectrum of background radiation coming from space and from the Earth environment. I observe every event being picked up by a Sodium Iodide detector and classify it according to its energy. I also calculate the fluxes of K-40, Tl-208 and muons γ rays, and evaluate the amount of energy loss per path lenght by muons in the NaI crystal. Being aware that not all events are picked up by the NaI detector, I use an Am-241 source to estimate the efficiency of the Sodium Iodide detector. I should note that the Am-241 smoke detector is also very useful to calibrate the energy scale of the multichannel analyzer software, Maestro[1].

INTRODUCTION

There are several types of cosmic and terrestrial ionizing radiation with which we are in contact every day of our life. One of the most abundant kinds of radiation in our universe is the Cosmic Microwave Background Radiation (or CMBR). The CMBR is thermal radiation filling the universe almost uniformly[2][Figure 1]. In particular, the cosmic background radiation is well explained as radiation left over from an early stage in the development of the universe, and its discovery is considered a landmark test of the Big Bang model of the universe[3]. CMBR is also very important because, as measured by the FIRAS instrument on the COBE, gives us the most precisely measured black body spectrum in nature[3][Figure 1]. Apart from the CMBR, other types of radiation can be found in the "medium" and "upper" part of the energy spectrum.

In this paper, I am going to focus on K-40 γ rays (≈ 1.5 MeV), Tl-208 γ rays (≈ 2.6 MeV) and cosmic ray muons (≈ 10 MeV). A sketch of the NaI spectrum is shown below in Figure 2.

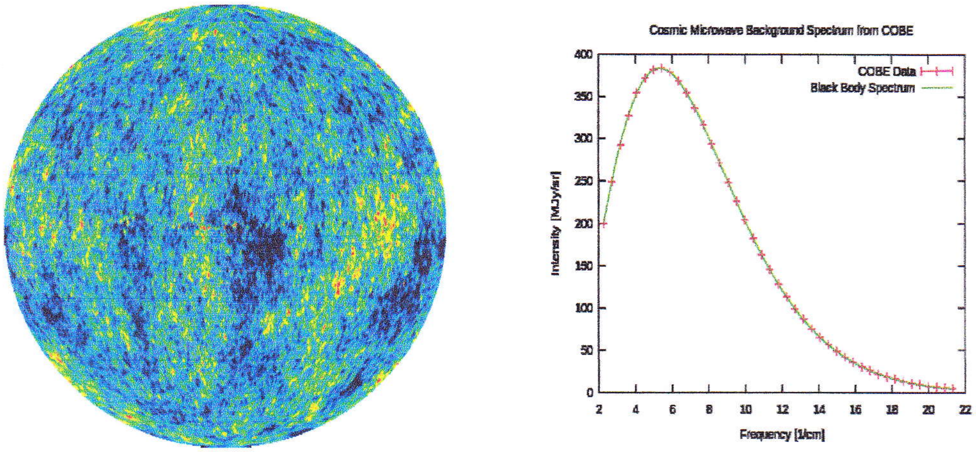

Figure 1: WMAP image of the CMBR temperature anisotropy (left)[3]. Graph of cosmic microwave background spectrum measured by the FIRAS instrument on the COBE (right)[3].

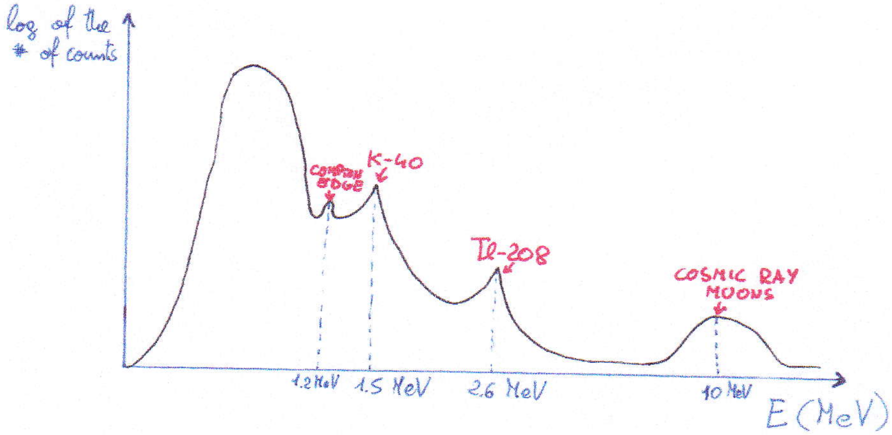

Figure 2: Sketch of the NaI radiation spectrum. The y-axis shows the log of the number of "counts" while the x-axis represents the energy in MeV.

Potassium-40 (^{40}K) is a radioactive isotope of potassium which has a very long half-life of $1.248 * 10^9$ years[5].

An interesting feature that we can observe right before the K-40 "protuberance" in the NaI spectrum is the so-called Compton edge. The Compton edge is a consequence of the Compton scattering in the NaI detector. In fact, when a γ ray scatters off the scintillator but escapes, only a fraction of its energy is registered by the detector[4]. This leads to a spectrum of γ rays in the data that is not really there[4]. The highest energy that occurs from this process is the Compton edge[4]. Using the Compton Effect formula, we can find the energy of the Compton Edge to be approximately equal to 1.2 MeV.

The Thallium-208 is a radioactive isotope with a very short half-life of 3.053 minutes[6]. It is interesting to notice that Tl-208 is the final product of a decay chain that starts with Th-232 (Thorium-232)[Figure 3].

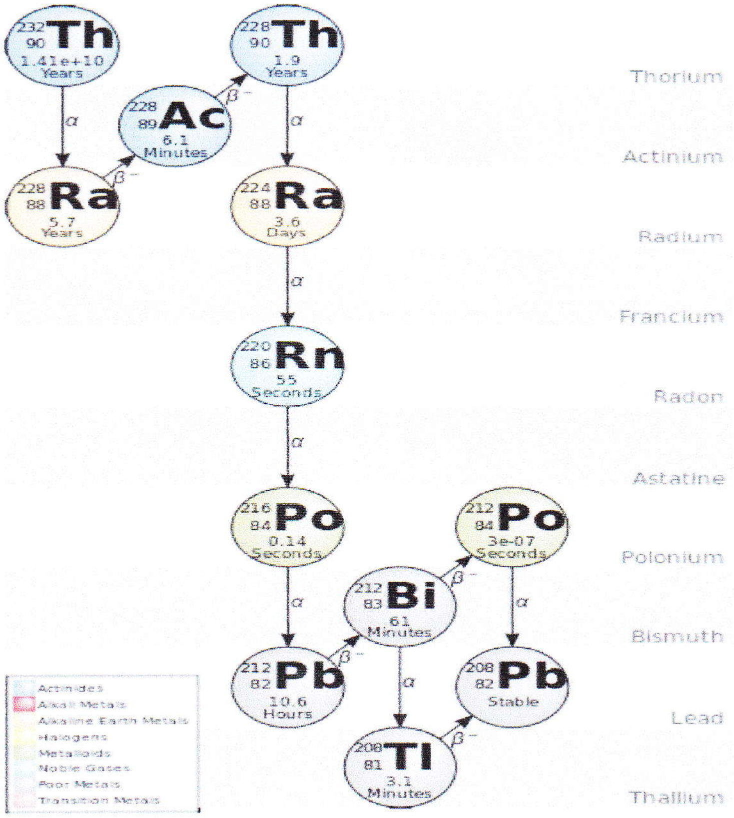

Figure 3: Decay chain of Th-232 leading to Tl-208[7]

The muon (a lepton) is an elementary particle similar to the electron, with unitary negative electric charge (−1) and a spin of 1/2[8]. The muon is an unstable subatomic particle with a mean lifetime of 2.2μs[8]. This comparatively long decay lifetime is due to being mediated by the weak interaction[8].

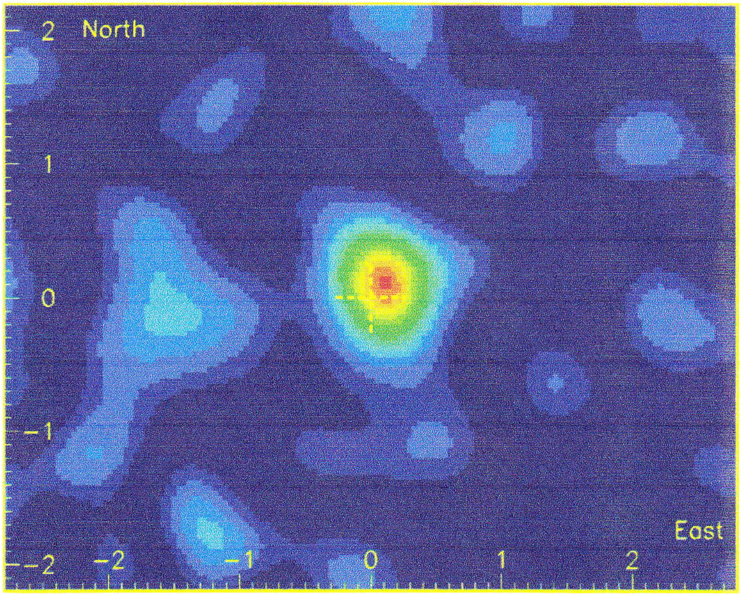

Figure 4: The Moon's cosmic ray shadow, as seen in secondary muons generated by cosmic rays in the atmosphere, and detected 700 meters below ground, at the Soudan II detector[8]

Another fascinating characteristic of the NaI spectrum is located between the Tl-208 and the cosmic ray muons. In this region of the spectrum, we can indeed observe cosmic ray electrons. Typically, cosmic ray electrons come in a great variety of energies and , as a result, are spread over a large portion of the energy spectrum. Moreover, if compared with other background radiation events we can observe, cosmic ray electrons are relatively rare. So, in order to be able to detect a good number of cosmic ray electrons, it is necessary to record data for at least one hour or more.

INSTRUMENTATION DESCRIPTION

This experiment has a few main components that are essential for its success. First of all, I use a sodium iodide scintillator crystal doped with thallium (or NaI(Tl)) to detect my electromagnetic signals. This NaI(Tl) detector is approximately 1.5 inch thick and has a 3 inch diameter. Secondly, an RCA 4900 3 inch diameter photomultiplier tube is attached to the NaI detector to pick up the light emitted by the scintillator and output an amplified electronic pulse[Figure 5].

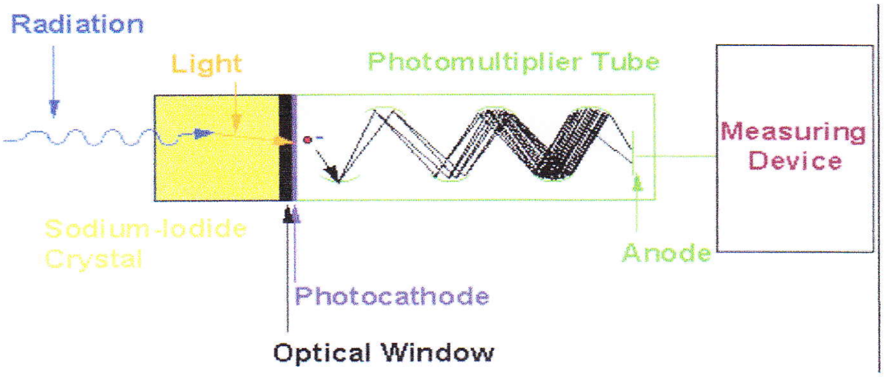

Figure 5: Schematic of Sodium-Iodide Crystal and Photomultiplier Tube[10].

This pulse then goes into an ORTEC preamplifier which acts as an interface between the detector and the pulse processing electronics that follow[9]. At this point, the pulse travels towards an ORTEC shaping amplifier[Figure 6], whose primary role is to magnify the amplitude of the preamplifier output pulse, filter out some of its noise and "shape" it to optimize the energy resolution and to minimize the risk of overlap between successive pulses[9]. Finally, our pulse goes into the ORTEC TRUMP PCI Multi-Channel Analyzer which is interfaced to a computer where the radiation signals can be easily analyzed with the aid of a software called MAESTRO[1].
I should mention that the preamplifier, the shaping amplifier and an high voltage power supply are all contained in one ORTEC ACE MATE box.

Figure 6: ORTEC AMPLIFIER on the left (includes the preamplifier, the shaping amplifier and an high voltage power supply). ORTEC TRUMP PCI Multi-Channel Analyzer on the right.

Besides the necessary equipment listed above, an oscilloscope might prove very useful to check that the apparatus of the experiment is working well and does not need "further adjusting". Figure 7 shows a picture of the lab setup. Going from the left to the right of Figure 7, it is possible to observe the oscilloscope, the photomultiplier tube with the NaI scintillator attached to its bottom, the amplifier and the PC where the data is analyzed.

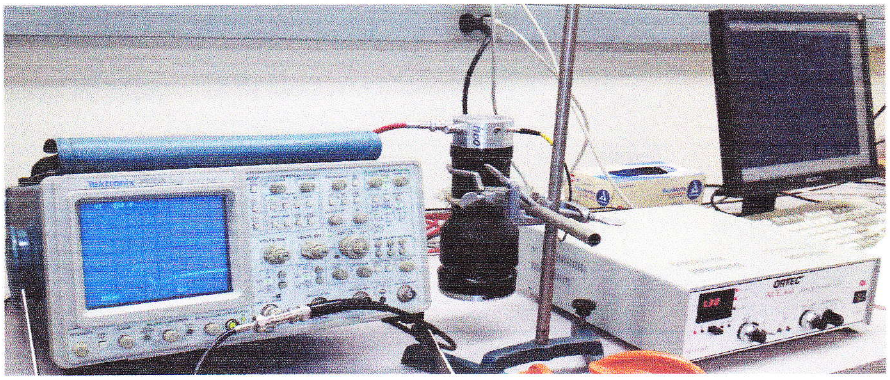

Figure 7: Lab setup: Oscilloscope, Photomultiplier with the NaI scintillator attached to its bottom, Amplifier and PC where the data is analyzed (from left to right).

SAFETY ISSUES

As I will explain in greater detail in the Data Taking Procedure section, a radioactive source needs to be used in order to calibrate the instrumentation discussed above. In my experiment, I use an Americium-241 radioactive source, which is commonly employed in smoke detectors in the form of americium dioxide as its source of ionizing radiation[11]. This isotope is preferred against ^{226}Ra because it emits 5 times more alpha particles and relatively little of harmful γ-radiation[11]. In particular, the decay process of ^{241}Am is the following: $^{241}_{95}Am \longrightarrow ^{237}_{93} Np +^{4}_{2} He + \gamma$ [11][Figure 8].

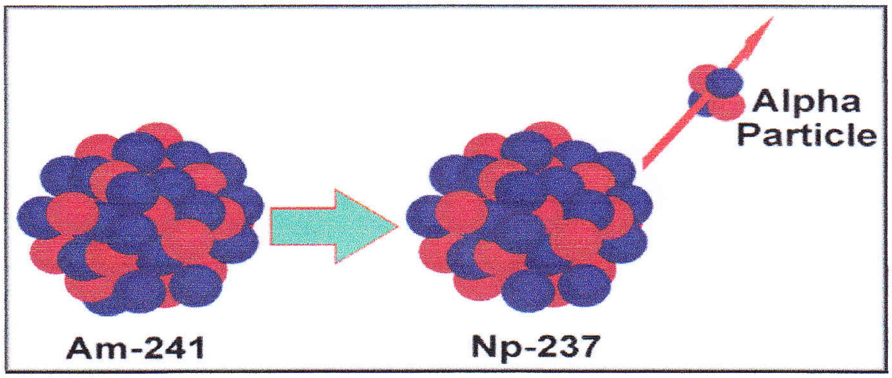

Figure 8: Americium-241 decay[12].

Americium-241 decays to ^{237}Np emitting alpha particles of 5 different energies, mostly at 5.486 MeV (85.2%) and 5.443 MeV (12.8%)[11]. Because many of the resulting states are metastable, they also emit gamma rays with the discrete energies between 26.3 and 158.5 KeV[11]. The amount of americium in a typical new smoke detector is 1 microcurie (37kBq) or 0.28 microgram[11]. This amount declines slowly as the americium decays into neptunium-237, a different transuranic element with a much longer half-life (about 2.14 million years)[11]. Pictures of the smoke detector that I used in my experiment are shown in Figure 9.

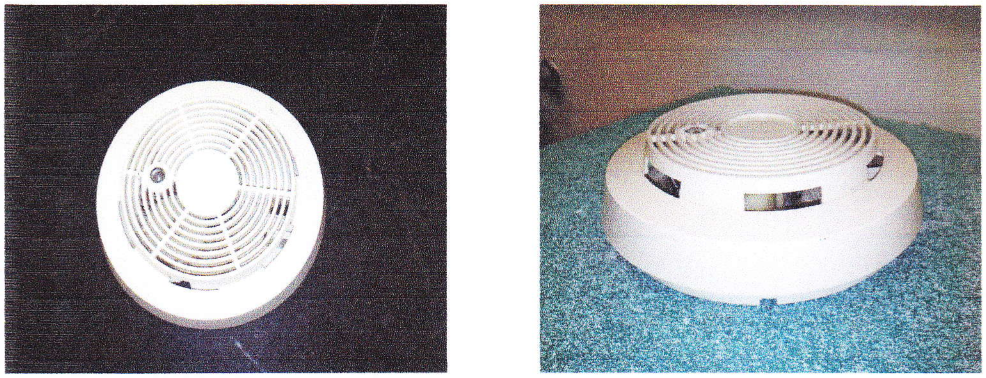

Figure 9: Pictures of the smoke detector that I used for my experiment[13]

The radioactive source that I used, unless ingested or inhaled for a prolonged period of time, is relatively safe. However, it is important to keep in mind that although most Americium isotopes predominantly emit alpha particles which can be blocked by thin layers of common materials, many of the daughter products emit gamma-rays and neutrons which have a long penetration depth[11]. That said, Americium-241 is one of the safest radioactive sources on the market to experiment with.
Another safety issue relevant to this experiment concerns the high voltage power supply inside the "ORTEC box" described in the Instrumentation Description section of this lab report. In particular a voltage of 1.3KeV is used throughout the experiment to power the photomultiplier tube. In fact, 1300V is the maximum voltage that the photomultiplier tube can take. It is very important to be very careful when turning on and off the experiment apparatus. The BIAS knob must be set to zero and the HV switch should be off before turning the power on[Figure 6]. Once the power is on, it is imperative to make sure that the switch under the ORTEC display is set to read KeV. After these basic precautions are taken, it is safe to turn the HV switch on and start adjusting the voltage. The voltage knob should be turned on very gently until the desired voltage is reached not to risk damaging the apparatus and incurring in other unnecessary dangers. The voltage should never be set higher than 1.3KeV at any point during the experiment. The "inverse" of the procedure described above should be carried out to turn off the experiment apparatus safely.

DATA TAKING PROCEDURE

Data taking is relatively easy thanks to the ORTEC MAESTRO software[1] which shows a graph of "counts" versus energy in real time. When enough data has been collected, one can stop the acquisition of data and save the final graph. It is also possible to change the energy scale by turning the COARSE GAIN knob on the ORTEC box[Figure 6] before starting a new acquisition. Higher values of gains correspond to smaller ranges of energy while smaller values of gains are associated to larger energy ranges. The ability of changing the gain is essential in this experiment. In fact, certain events can only be observed under specific gains. For example, we will never be able to observe cosmic ray muons if we set our gain to 100 because the energy range would be too small to detect energies bigger than the "upper limit" of our energy range. Moreover, changing gain can be a good way of testing that our previous measurements "agree" with the new ones.
As I have already mentioned in one of the previous sections, the apparatus is calibrated using an Americium-241 radioactive source. The reason for this is that the energy spectrum of the NaI crystal is known and it is characterized by a photopeak and a so-called "escape peak"[Figure 10]. The photopeak is caused by 60KeV x-rays, coming from the Am-241 source, that are completely absorbed in the NaI scintillator by photoelectric process[14].

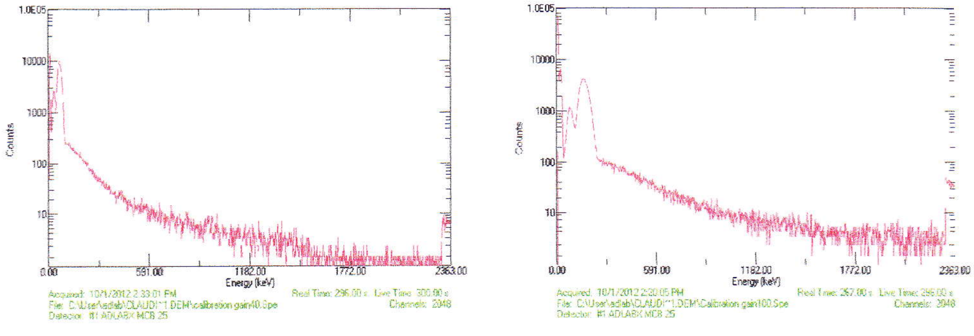

Figure 10: Calibrations with gain=40 (left) and gain=100 (right).

After photoelectric absorption, the iodine K-shell characteristic X-rays (28KeV) escape from the crystal so that the measured x-ray energy is only 32KeV

(60 − 28)KeV[14]. This will cause a peak, usually called as iodine escape peak[14]. It is important to observe that the energy scales of the graphs that I am going to present in this lab report are off by a factor, which can be easily determined thanks to our knowledge of the NaI crystal (discussed above). My off-scale readings for the energies of the photopeak and the iodine escape peak of the NaI crystal were 160.38KeV and 78.46KeV respectively (with gain=100). On the other hand, when I set my gain to 40, the off-scale energies for the photopeak and the iodine escape peak turned out to be 64.62KeV and 32.31KeV respectively. So, given that the true energy of the photopeak is 60KeV, one can try to estimate the energy of the iodine escape peak using the information above. Specifically, we find $E_{escapepeak100} = \frac{60KeV*78.46KeV}{160.38KeV} \approx 29.35KeV$ (gain=100) and $E_{escapepeak40} = \frac{60KeV*32.31KeV}{64.62KeV} \approx 30KeV$ (gain=40). These values are pretty close to the real escape peak energy value of 32KeV. The main sources of error for the approximate energy values calculated above come from the fact that I had to decide "manually" where the graphs' peaks were. Also, the "energy bins" used in the MAESTRO software are discrete and have a finite size or energy resolution. In any case, calibrating my experiment apparatus with an Americium-241 radioactive source has proved to be an effective way of checking that everything works correctly.

Another useful tool in the MAESTRO software are the so-called markers. Markers represent a method of numbering or counting the energy bins in my acquisition graphs. Of course, each energy bin "gets bigger" (or contains a wider energy gap) as the gain is decreased. When I set my gain to 100, the photopeak and escape peak for my NaI crystal occured for markers 139 and 68 respectively. However, when my gain was set at 40 the photopeak and escape peak of the NaI detector moved to markers 56 and 28 respectively. Having this information, I can think of at least four different ways of calculating my radiation energies, given a gain and a marker: $E \approx \frac{marker*60KeV}{139} * \frac{100}{gain} \approx \frac{marker*32KeV}{68} * \frac{100}{gain} \approx \frac{marker*60KeV}{56} * \frac{40}{gain} \approx \frac{marker*32KeV}{28} * \frac{40}{gain}$. It makes sense to use the mean of these four formulas. This average turns out to be $E_{\mu} \approx \frac{marker}{gain} * 44.699$.

DATA ANALYSIS

Once I terminated my calibrations, I removed the Americium-241 radioactive source from the vicinity of the NaI crystal and started collecting data on the cosmic and terrestrial ionizing radiation. I collected 6 sets of data corresponding to 6 different gains: 2,4,10,20,40,100. The runs for gains 2,4,10 and 20 lasted approximately 1 hour. On the other hand, the data acquisition for gains 40 and 100 lasted 2 and 1.33 hours respectively. So, I used the technique explained in the Data Taking Procedure section of this paper to analyze my graphs. When I set my gain to 20 I could identify K-40 and Tl-208 events[Figure 11]. When I lowered my gain even further down to 10, I could also observe cosmic ray muons[Figure 11].

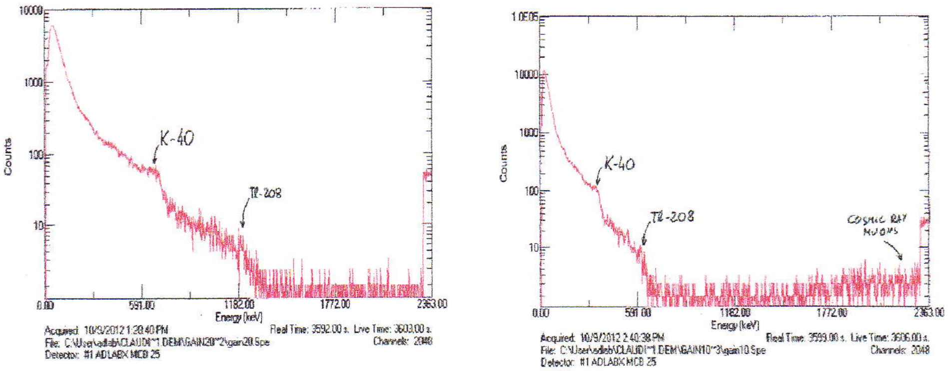

Figure 11: Energy spectrum for gain 20 (left) and for gain 10 (right).

At some point, I decided to lower my gain down to 2 and 4[Figure 12]. Besides seeing the "muons bump region" much better than before, I could also observe cosmic ray electrons which are usually much harder to see.

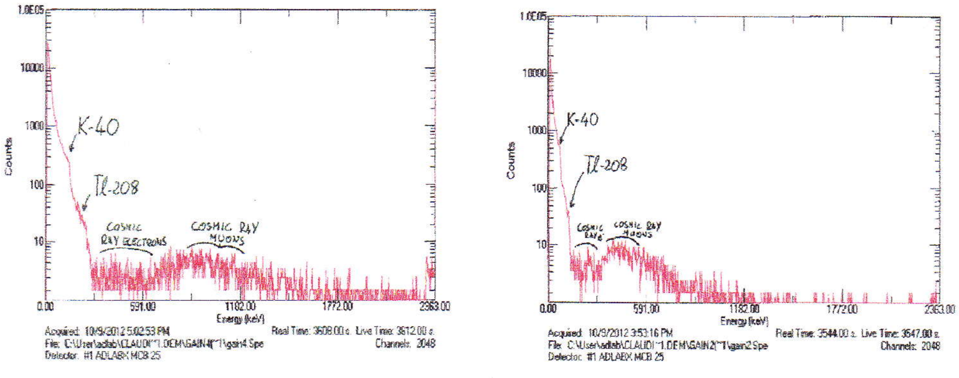

Figure 12: Energy spectrum for gain 4 (left) and for gain 2 (right).

I could not identify anything with gain settings of 40 and 100[Figure 13]. This is probably because the energy range was too small and the data collected in the upper part of the energy spectrum was not very good.

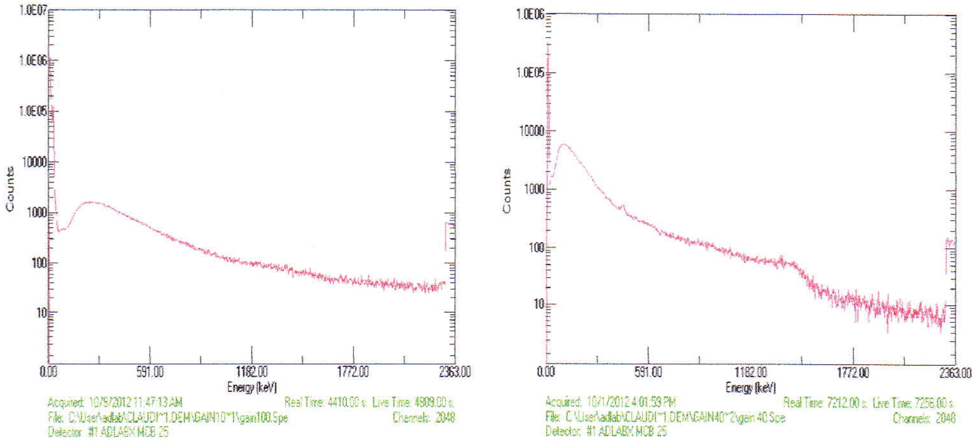

Figure 13: Energy spectrum for gain 100 (left) and for gain 40 (right).

CONCLUSIONS

Now, I am going to estimate the fluxes of my background radiation events as a function as a function of energy on a flat surface in units of $\frac{counts}{cm^2*s}$. In paricular, I am going to use the circular area of my NaI crystal. Given that the radius of the crystal is approximately equal to $r \approx 3.81cm$, its area will be given by $A \approx 45.6cm^2$. I should point out that here I simply calculate the fluxes corresponding to the "peaks" of my background radiation events. The reason for this is to give an idea of how these fluxes depend on the radiation energy[Figure 14]. So, it is important to keep in mind that each one of these events occurs for a range of energies (as opposed to one energy). As a result, the "real fluxes" would be considerably higher than what I calculated below (especially for muons). Also, it is considerably hard and tedious to sum all the counts for each range of energy because of limitations in the MCA software that I used.

My averaged "radiation peaks' fluxes" for K-40, Tl-208 and muons turned out to be $\phi_{K-40} \approx 6.2*10^{-2}\frac{counts}{s*cm^2}$ $(E_{K-40} \approx 1.33MeV)$, $\phi_{Tl-208} \approx 0.6*10^{-2}\frac{counts}{s*cm^2}$ $(E_{Tl-208} \approx 2.28MeV)$, $\phi_{muons} \approx 0.4*10^{-2}\frac{counts}{s*cm^2}$ $(E_{muons} \approx 9.25MeV)$ respectively.

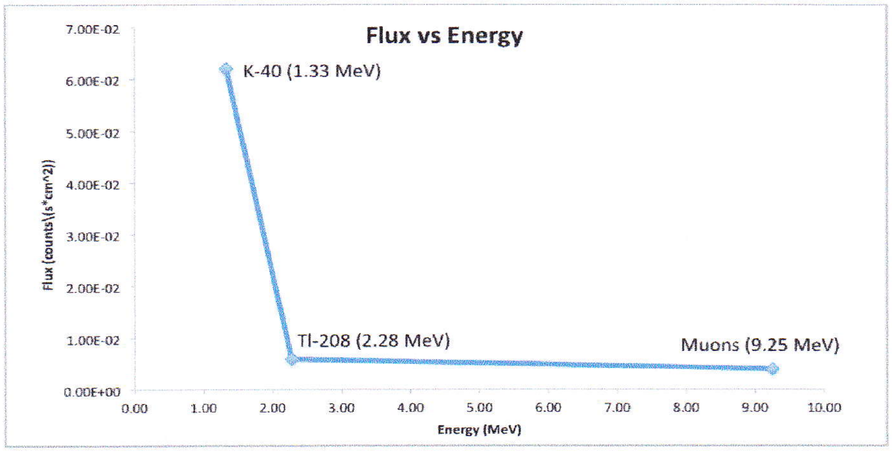

Figure 14: Flux as a function of energy (MeV) on a flat surface in units of $\frac{counts}{s*cm^2}$ for $K-40$, $Tl-208$ and cosmic ray muons.

We can observe right away from the graph above that as energy increases the flux decreases. In particular, it is hard to miss the "big jump" from $K-40$ to $Tl-208$, which is notably larger than the flux difference bewtween $Tl-208$ and the cosmic ray muons.
We can also estimate the amount of energy loss per path lenght by muons in the NaI crystal using Bethe formula[15]:

$$-(\frac{dE}{dx}) = (\frac{4\pi}{m_ec^2}) \cdot (\frac{nz^2}{\beta^2}) \cdot (\frac{e^2}{4\pi\epsilon_0})^2 \cdot [ln((\frac{2m_ec^2\beta^2}{I\cdot(1-\beta^2)}) - \beta^2] \text{ [15]}$$

where v is the velocity of the muon, c is the speed of light, $\beta = \frac{v}{c}$, E is the energy of the muon, x is the distance travelled by the muon, z is the muon charge, e is the charge of the electron, m_e is the rest mass of the electron, n is the electron density of the NaI crystal, I is the mean excitation potential of the NaI target and ϵ_0 is the vacuum permittivity[15]. The electron density of the NaI crystal can be calculated by $n = \frac{N_A*Z*\rho}{A*M_u}$ where ρ is the density of the material, Z,A its atomic and mass number, respectively, N_A the Avogadro number and M_u the Molar mass constant[15]. In 1993 Felix Bloch showed that the mean ionization potential of atoms is approximately given by $I = (10eV) * Z$ where Z is the atomic number of the atoms of the material[15]. For a sodium iodide crystal we have $\rho \approx 3.667\frac{g}{cm^3}$, $Z = 53$, $A = 126.9$, $M_u = 149.89\frac{g}{mol}$ and $E_{muon} \approx 9.25MeV$. Unfortunately, it is known that Bethe formula does not work very well with low energy muons (as the muons observed in my experiment). In any case, Bethe equation can be reduced in the following way[16]:

$$-\frac{1}{\rho}\frac{dE}{dx} = (\frac{z}{e})^2(0.153\frac{MeV*cm^2}{g})\frac{1}{\beta^2}[ln((\frac{2m_ec^2\beta^2}{I\cdot(1-\beta^2)}) - \beta^2]$$

In our case we have $z^2 = e^2$ and $\beta \approx 0.42$ ($9.25MeV$ muons). So, I calculated the energy loss per path lenght by muons in a sodium iodide crystal to be $\frac{dE}{dx} \approx -4.2\frac{MeV*cm^2}{g} * \rho_{NaI} \approx -15.4\frac{MeV}{cm}$. This would suggest that the approximately $9MeV$ muons that I detected were considerably more energetic right before entering the NaI scintillator and lost a good part of their energy inside the detector. It is useful to compare this result with the one that Groom, Mokhov and Striganov managed to find in their paper.[17]. Groom's approximation, which is valid for the energy range $10MeV - 100TeV$ is given by $< -\frac{1}{\rho}\frac{dE}{dx} >_{min} \approx 1.305\frac{MeV*cm^2}{g}$ where $< -\frac{1}{\rho}\frac{dE}{dx} >_{min}$ represents the minimum value of the energy loss per path lenght that Groom, Mokhov and Striganov found[17].

Another interesting thing to calculate is the efficiency of the NaI scintillator. The MAESTRO software "splits" the energy in the graph in 2000 energy bins. When the gain is set to 40, each energy bin is approximately $1.18KeV$ wide. Using this information, it is possible to make a very rough approximation (by ruler) of the total number of "detected" counts in the photopeak and escape peak of the sodium iodide crystal. I found approximately 500000 "detected" counts for a 5 minutes gain-40 run. This would equal $1666\frac{counts}{s}$. The Americium-241 in a typical smoke detector has $37000\frac{disintegrations}{s}$. However, the Am-241 radioactice source emits $60KeV$ x-rays only 30 percent of the time. Finally, the efficiency of the NaI crystal is approximately equal to $\eta \approx \frac{1666}{37000*0.3} * 100 \approx 15\%$. This is probably less than the real NaI detector efficiency because I rounded down my approximation of the total number of "detected" counts.

Cosmic and terrestrial ionizing radiation is everywhere and comes in several "types". In this lab report, I only observed a relatively small part of the energy spectrum $(0 - 10MeV)$. It would be very interesting to analyze a much more energetic muons region where the Bethe formula (discussed above) becomes a very good approximation. Also, due to the limits of my experiment apparatus, I could not resolve some details of the "fine structure" of the energy spectrum such as the Compton edge (discussed in the Introduction section) and a few others.

References

[1] MAESTRO by ORTEC®. Website: www.ortec-online.com/Solutions/multichannel-analyzers.aspx.

[2] Penzias,A.A.;Wilson,R.W.(1965). "A Measurement of Excess Antenna Temperature at 4080 Mc/s". Astrophysics Journal **142**:419-421.

[3] Wikipedia. URL: en.wikipedia.org/wiki/Cosmic_microwave_background_radiation.

[4] Wikipedia. URL: en.wikipedia.org/wiki/Compton_edge.

[5] Wikipedia. URL: en.wikipedia.org/wiki/Potassium-40.

[6] WWW Table of Radioactive Isotopes. URL: ie.lbl.gov/toi/nuclide.asp?iZa=810208.

[7] Wikipedia. URL: en.wikipedia.org/wiki/Thorium.

[8] Wikipedia. URL: en.wikipedia.org/wiki/Muon.

[9] Med Phys 4R06/6R03. Radioisotopes and Radiation Methodology. Chapter 6 Pulse Processing. Website: www.science.mcmaster.ca/medphys/images/files/courses/4R06/note6.pdf.

[10] Measurement of Radiation,Sodium Iodide Detector. Website: www.physics.isu.edu/radinf/naidetector.htm.

[11] Wikipedia. URL: en.wikipedia.org/wiki/Americium.

[12] ORACLE ThinkQuest EDUCATION FOUNDATION. Three Types of Radioactive Decay. URL: library.thinkquest.org/3471/radiation_types_body.html.

[13] The picture of the smoke detector on the right was taken by Joshua Gray.

[14] K Thayalan. Basic Radiological Physics (JAYPEE). Pag.164.

[15] Wikipedia. URL: en.wikipedia.org/wiki/Bethe_formula.

[16] This approximation of Bethe equation was presented during lecture by Dr.Steve Ahlen on October 8th 2012.

[17] Donald E.Groom (Ernest Orlando Lawrence Berkley National Laboratory), Nikolai V.Mokhov (Fermi National Accelerator Laboratory), Sergei I.Striganov (Fermi National Accelerator Laboratory). MUON STOPPING POWER AND RANGE TABLES.