The Detection of Cosmic Rays

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ABSTRACT

We reproduce Bruno Rossi's 1933 experiment on the detection of cosmic rays. We use a simple apparatus consisting of two Geiger counter tubes, a lead incasing with a variable thickness roof, and coincidence counter electronics. We confirm that coincident counts, indicative of cosmic rays, result from two competing effects: the aptitude of cosmic rays to penetrate a given thickness of lead and the aptitude for a cosmic ray to create a shower of particles due to its interaction with a given thickness of lead.

1. Introduction

Cosmic rays are energetic particles that originate from outside earth's atmosphere. Being mostly light, atomic nuclei, cosmic rays are thought to originate from supernova explosions although this fact has not been observationally confirmed. The world's largest high energy cosmic ray detector, coving many square kilometers in Argentina, is the Pierre-Auger observatory. Recently, that telescope has hinted at the possibility that cosmic rays originate from highly energetic extragalactic sources, not necessarily just supernovae (The Pierre Auger Collaboration et al. 2007).

Cosmic rays were not found to be outside earth's atmosphere until the 1912 balloon experiment by Victor F. Hess at an altitude of 5000 m, and it was not until 1933 that Bruno Rossi confirmed that cosmic rays are energetic enough to interact with earth's atmosphere and even with lead of thicknesses ∼cm (Jackson & Welker 2001). See Figure 1 for the distribution of cosmic ray fluxes for given energies in eV[1].

Cosmic rays shower into many particles due to their interaction with earth's atmo-

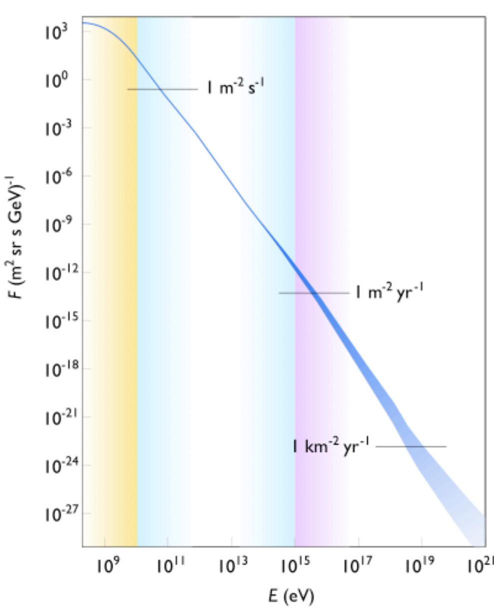

Fig. 1.— The cosmic ray flux at varies energies in eV.

[1] http://upload.wikimedia.org/wikipedia/commons/8/8b/Cosmic ray flux versus particle energy.svg

sphere or even with lead. Figure 2 shows how a high energy primary can shower into three different types of showers, which in turn cascade even further. Figure 3 is a cloud chamber, in which cloud particles condense due to energetic particles' perturbations, which also shows a cosmic ray shower. The three types of showers are the meson shower, nucleon cascade, and electromagnetic shower (Jackson & Welker 2001).

1.1. Nucleon Coscade & Meson Shower

The nucleon cascade consists of particles from the initial interaction of the cosmic ray with earth's atmosphere. From this interaction, pions (π), with a 10^{-8} s lifetime, are created. Pions decay into muons via the reaction $\pi^{\pm} \rightarrow \mu^{\pm} + \nu(\bar{\nu})$. Since the muons cannot decay fast enough via the reaction $\mu^{\pm} \rightarrow e^{\pm} + \nu + \bar{\nu}$, many of them survive by the time they reach the ground. Pions and muons comprise the meson shower.

1.2. Electromagnetic Shower

Pair production, the reaction $\gamma \rightarrow e^{+} + e^{-}$; neutral pion decay, the reaction $\mu^{0} \rightarrow 2\gamma$; and bremsstrahlung or free-free emission, the reaction $e^{\pm} \rightarrow e^{\pm} + \gamma$ all contribute to the electromagnetic cascade.

2. Experimental Setup & Procedure

Shown in Figure 4 is our experimental setup. It consists of two simple Geiger tubes, such as those in Figure 5[2], connected to a single channel analyzer circuit, which cleans up and amplifies the Geiger counter signals' pulses. From the single channel analyzer we fed the amplified signal to a counter circuit which electronically increments a number for each Geiger counter pulse. We also connected a coincidence counter which counts how many Geiger counter pulses occurred within a small time interval of one another. These coincidences are indicative of cosmic ray showers because only a shower is most likely to trigger both Geiger counters simultaneously.

For each thickness of the lead enclosure's roof, we recorded the number of single counts each of our Geiger counter registered as well as the coincidence in counts between the two Geiger counters. From these data we computed the number of counts per hour, taking into account the fact that errors in Poisson distributions are proportional to the $\sqrt{N}$, where N is the number of counts detected. Because we sampled many events, our errors due to Poisson statistics are very small.

3. Theory

According to the simple derivation of Jackson & Welker (2001), single counts N_{single} as a function of lead thickness x should obey the law

$$N_{\text{single}} = N_{ni} + N_i e^{-\mu x}, \tag{1}$$

where N_{ni} is the component of the counts that does not interact with the lead, N_i is the interacting component, and μ is a free parameter.

The second equation that Jackson & Welker (2001) derive is that of the coincidences N_{cc} as a function of lead thickness x. It states that

$$N_{cc} = N_{as} + PN_0(1 - e^{-\beta x})e^{-\mu x}, \tag{2}$$

where N_{as} is a component due to the atmospheric muons, P is the probability that an shower is detected by the Geiger counters, and β is a free parameter.

4. Analysis and Results

Shown in Table 1 are our raw data.

Figures 6 and 7 show the single counts from RM1 and RM2 Geiger counters. The first counter did not obey the law of Equation 1 as did the second counter. This may be due

[2] http://upload.wikimedia.org/wikipedia/commons/f/f0/Geiger.png

Table 1
Experimental Results

RM1 Counts	RM2 Counts	Coincidences	Integration Time (s)	Lead Thickness (mm)
46708	69222	199	82011.7 ± 0.1	4.85 ± 0.05
58203	156858	261	91224.4 ± 0.1	7.75 ± 0.05
51281	51059	231	82196.9 ± 0.1	18.7 ± 0.05
166615	241743	688	258835.0 ± 0.1	29.1 ± 0.05
112471	69361	424	172800.0 ± 14400	35.0 ± 0.05
50526	36334	174	85713.1 ± 0.1	39.8 ± 0.05
53017	35652	152	86569.9 ± 0.1	$47.0 \pm 6.$
207357	148441	669	345092.0 ± 0.1	51.0 ± 0.05

Note.—Two of our data points suffered larger errors than normal in the lead thickness and integration timing measurements due to human error.

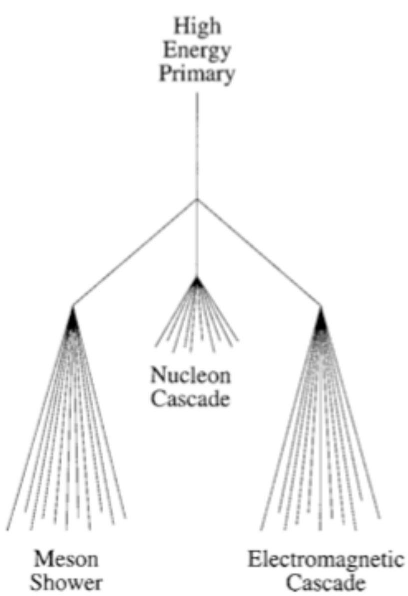

Fig. 2.— Cosmic ray shower from Jackson & Welker (2001)

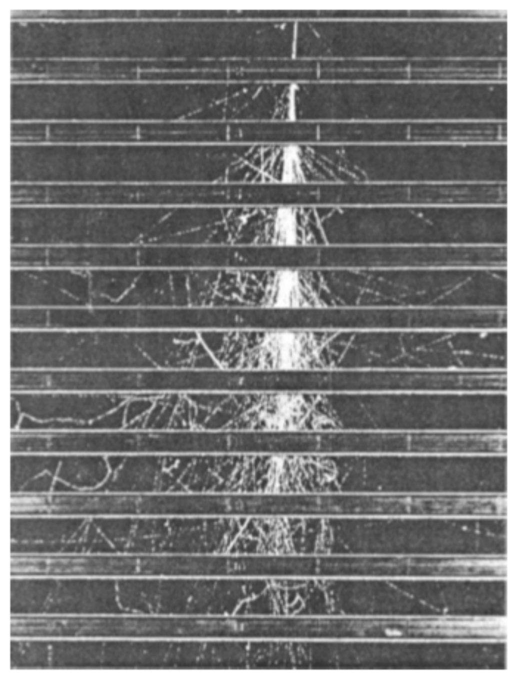

Fig. 3.— Cloud chamber representation of cosmic ray shower Jackson & Welker (2001)

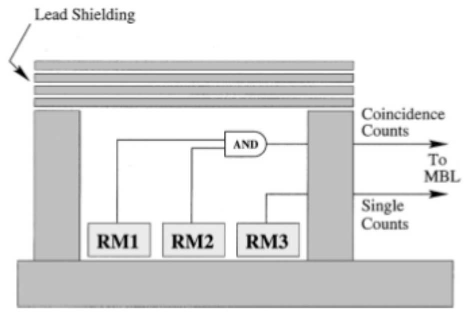

Fig. 4.— Our experimental setup. RM signifies "radiation monitor," which in our case were Geiger tubes. We did not use the third RM, RM3. (Jackson & Welker 2001)

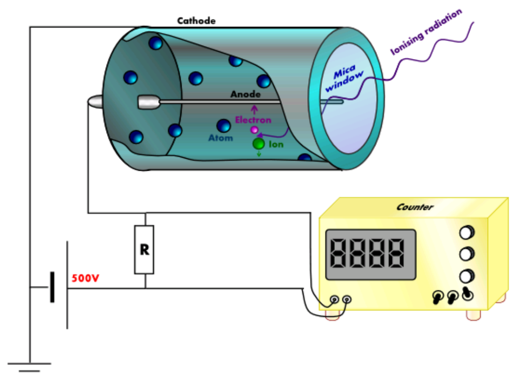

Fig. 5.— Geiger tubes such as those used in our experiment. The figure shows voltages of ∼500 V, which is similar to the voltages at which we drove our tubes.

to the fact that the second counter's voltage was stabler than that of the first. Figure 8 shows the ratio of the counters' single counts, again as a function of the lead thickness x. Because this graph is not unity, there were systematic errors introduced into our measurements. Had our Geiger counters been calibrated better and remained stable, our single counts would have looked like Figure 9.

For our coincidences, we observed behavior like that of Equation 2 as shown in Figure 10. It peaked at low lead thickness due to the competing effects of more lead thickness blocking out lower energetic particles and more lead thickness increasing the interaction cross section for showering due to the lead.

For reference, we show Rossi's results in Figure 11. Rossi used three Geiger counters instead of our two.

5. Conclusion

Although there is only one point in Figure 10 that shows a turnover in the coincidence versus lead thickness trend, we interpret this as real and not due to any systematic uncertainties. Because the error bars are overly small, due to our long integration times per lead thickness, it would have been better to take more points just to see if our first data point in Figure 10 is an outlier or not. Nevertheless, the we do believe that, despite our

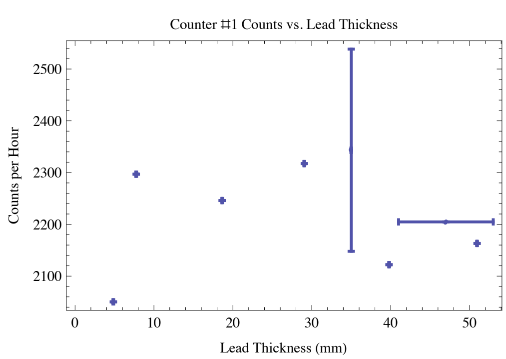

Fig. 6.— Single counts for RM1

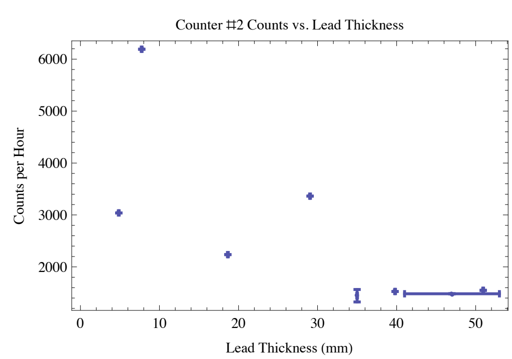

Fig. 7.— Single counts for RM2

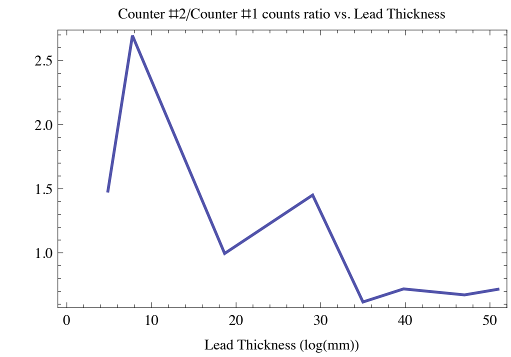

Fig. 8.— Ratio of RM1 and RM2 counts

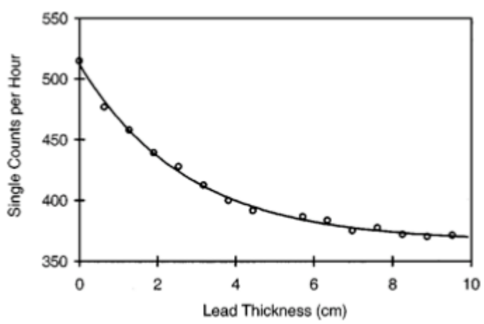

Fig. 9.— Expected single counts from Jackson & Welker (2001)

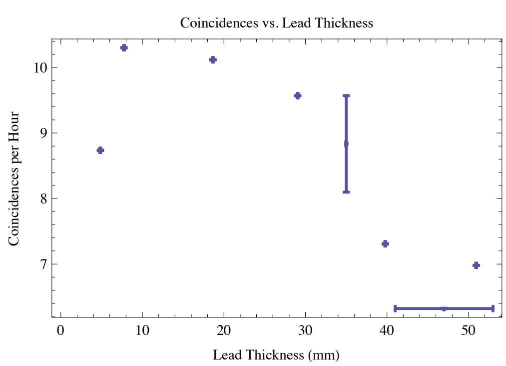

Fig. 10.— Measured coincidences

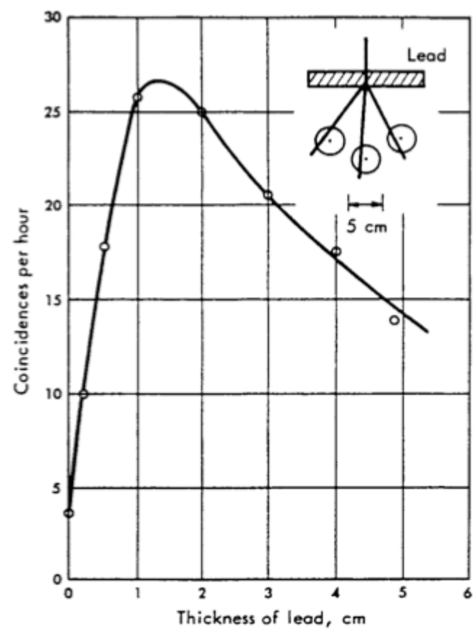

Fig. 11.— The Rossi experiment's coincidences

seeming scatter plots (Figures 6 and 7), both the laws of Equations 1 and 2 are obeyed.

REFERENCES

The Pierre Auger Collaboration, et al. 2007, Science, 318, 938

Jackson, D. P., & Welker, M. T. 2001, American Journal of Physics, 69, 896

This 2-column preprint was prepared with the AAS LaTeX macros v5.2.

A. *Mathematica* plotting commands

We used *Mathematica* to generate the plots in this paper. The following *Mathematica* commands also illustrate how we propagated Poisson and measurement errors.

```
Needs["ErrorBarPlots`"]

TableForm[
 data = ReadList[
   SystemDialogInput["FileOpen"], {Number, Number, Number, Number,
    Number, Number, Number}]]

ErrorListPlot[
 plotlist =
  Table[{{data[[x, 6]], data[[x, 3]]/(data[[x, 4]]/3600)},
    ErrorBar[data[[x, 7]],
     data[[x, 3]]/(data[[x, 4]]/3600) Sqrt[
      1/data[[x, 3]]^3 + (data[[x, 5]]/data[[x, 4]])^2]]}, {x, 1, 8}],
  PlotStyle -> Thick,
 FrameLabel -> {{"Coincidences per Hour",
    Null}, {"Lead Thickness (mm)",
    "Coincidences vs. Lead Thickness"}}, Frame -> True,
 Axes -> False]

ErrorListPlot[
 Table[{Log[10, {data[[x, 6]], data[[x, 3]]/(data[[x, 4]]/3600)}],
   ErrorBar[data[[x, 7]],
    data[[x, 3]]/(data[[x, 4]]/3600) Sqrt[
     1/data[[x, 3]]^3 + (data[[x, 5]]/data[[x, 4]])^2]]}, {x, 1, 8}],
 PlotStyle -> Thick,
 FrameLabel -> {{"log(Coincidences per Hour)",
    Null}, {"Lead Thickness (log(mm))",
    "Coincidences vs. Lead Thickness"}}, Frame -> True,
 Axes -> False]

ErrorListPlot[
 counter1 =
  Table[{{data[[x, 6]], data[[x, 1]]/(data[[x, 4]]/3600)},
    ErrorBar[data[[x, 7]],
     data[[x, 1]]/(data[[x, 4]]/3600) Sqrt[
      1/data[[x, 1]]^3 + (data[[x, 5]]/data[[x, 4]])^2]]}, {x, 1, 8}],
  PlotStyle -> Thick,
 FrameLabel -> {{"Counts per Hour", Null}, {"Lead Thickness (mm)",
    "Counter #1 Counts vs. Lead Thickness"}}, Frame -> True,
 Axes -> False]

ErrorListPlot[
```

```
 Table[{Log[10, {data[[x, 6]], data[[x, 1]]/(data[[x, 4]]/3600)}],
   ErrorBar[data[[x, 7]],
    data[[x, 1]]/(data[[x, 4]]/3600) Sqrt[
     1/data[[x, 1]]^3 + (data[[x, 5]]/data[[x, 4]])^2]]}, {x, 1, 8}],
 PlotStyle -> Thick,
 FrameLabel -> {{"log(Counts per Hour)",
    Null}, {"Lead Thickness (log(mm))",
    "Counter #1 Counts vs. Lead Thickness"}}, Frame -> True,
 Axes -> False]

ErrorListPlot[
 counter2 =
  Table[{{data[[x, 6]], data[[x, 2]]/(data[[x, 4]]/3600)},
    ErrorBar[data[[x, 7]],
     data[[x, 2]]/(data[[x, 4]]/3600) Sqrt[
      1/data[[x, 2]]^3 + (data[[x, 5]]/data[[x, 4]])^2]]}, {x, 1, 8}],
  PlotStyle -> Thick,
 FrameLabel -> {{"Counts per Hour", Null}, {"Lead Thickness (mm)",
    "Counter #2 Counts vs. Lead Thickness"}}, Frame -> True,
 Axes -> False]

ErrorListPlot[
 Table[{Log[10, {data[[x, 6]], data[[x, 2]]/(data[[x, 4]]/3600)}],
   ErrorBar[data[[x, 7]],
    data[[x, 2]]/(data[[x, 4]]/3600) Sqrt[
     1/data[[x, 2]]^3 + (data[[x, 5]]/data[[x, 4]])^2]]}, {x, 1, 8}],
 PlotStyle -> Thick,
 FrameLabel -> {{"log(Counts per Hour)",
    Null}, {"Lead Thickness (log(mm))",
    "Counter #2 Counts vs. Lead Thickness"}}, Frame -> True,
 Axes -> False]

ListPlot[Table[{data[[x, 6]], data[[x, 2]]/data[[x, 1]]}, {x, 1, 8}],
 PlotStyle -> Thick,
 FrameLabel -> {{Null, Null}, {"Lead Thickness (log(mm))",
    "Counter #2/Counter #1 counts ratio vs. Lead Thickness"}},
 Frame -> True, Axes -> False, Joined -> True]
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