

Seasonal Variations in Soudan 2

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Abstract

Seasonal Variations in an underground detector may be a signature for Dark Matter.[1] The Soudan 2 detector searches for nucleon decay and atmospheric neutrinos. The trigger rate is about 0.5 Hertz. It is dominated by approximately equal numbers of atmospheric muons and low level radioactivity. The muon rate has a seasonal variation of $\pm 2\%$, which is consistent with a similar effect at MACRO. The MACRO effect has been correlated with temperature in the upper atmosphere. Our trigger rate has a seasonal variation of $\pm 15\%$ which we believe is due to radon in the mine, and variations in air flow with outside temperature.

1 Introduction

Soudan 2 has measured clear seasonal variations in both its muon rate and its trigger rate. The $\sim 5\%$ rise in the muon rate has also been seen in other experiments, and is understood as an effect due to seasonal changes in temperature in the upper atmosphere. The average temperature change between summer and winter is $\sim 30^\circ\text{K}$. At a point of fixed pressure in the atmosphere (i.e. fixed overburden), this $\pm 2\%$ change in the temperature results in a $\pm 2\%$ change in the local density. The competition between pion absorption and pion decay favors absorption when the density is high (winter) and the fraction of pions which decay to give a muon goes down.

The $\sim 30\%$ rise in the trigger rate during the summer was harder to understand. Some dark matter experiments use a seasonal variation as a potential signature for dark matter. If the mean velocity of dark matter is at rest in the galaxy, then the relative velocity between the earth and the dark matter increases (decreases) as the earth's motion around the sun is parallel (antiparallel) with the motion of the sun around the galaxy. For no particular reason, these periods of time roughly correspond to summer and winter. Dark matter cross sections are expected to be proportional to relative velocity. Another suggested cause for the seasonal variation was electrical noise variations, due to increased cage rides and other activities during the tourist season. If this explanation was correct, a strong day-night effect during the summer would be expected. We now believe the trigger variation is due to radon. The airborne radon level in the mine is higher in the summer than the winter because there are different patterns of ventilation in the mine depending on the relative inside/outside temperatures. This effect has been seen in other caves and mines, and is consistent with measurements of the radon near Soudan 2.

2 Seasonal Variations in the Muon Rate

Seasonal changes in muon rates have been reported at previous Cosmic Ray Conferences.[2] The atmosphere gets colder as one goes up in altitude. Protons arriving from outer space go about an interaction length where they make secondary pions. The pions then may interact or decay within an interaction length. A larger number of π 's and μ 's are made deeper in the shower, but the highest energy ones come from the first few interactions. Since the energy spectrum of cosmic rays is steeply falling, a muon observed underground is likely to come from a primary with an energy within a factor of 10 of the energy of the primary.

At a fixed height, when the temperature changes, the pressure and density both change. But pion production by cosmic rays depends not on altitude but on overburden. Thus in the comparison of muon production rates, we consider what happens as the temperature changes for a point with a

constant overburden, which corresponds to a point of constant pressure. In an ideal gas, for a point of constant pressure, the density is inversely proportional to the temperature. Muon production from pion decay is favored in regions of low density and suppressed relative to absorption in regions of high density. This same mechanism which leads to the $\sec\theta$ effect on the angular distribution of underground muons is responsible for the seasonal effect of muons.

MACRO[3] parameterized the change in muon rate

$$\Delta R_\mu/R_\mu = \alpha_T \Delta T_{eff}/\bar{T}_{eff} \quad (1)$$

where α_T is the depth-weighted temperature coefficient, and \bar{T}_{eff} is the average effective temperature during the data taking period. The effective temperature is difficult to evaluate in general. However for the case in which the observed muons come from pion decay alone, a simple expression for T_{eff} depends on the atmospheric attenuation length for pions and nucleons. The general features of the Soudan data and the MACRO data are similar. There is a seasonal variation of $\pm 2\%$. Since we do not presently have high altitude temperature data near Soudan with which to compare, we have not extracted a value of α_T from the Soudan data. However, if the temperature data is similar to MACRO, which is reasonable to a first approximation, then a similar value of α_T would be found. This is consistent with the expectation from Figure 6 in Reference [3].

Note that there is no reason a-priori that the temperature variation should be the same from year to year. We have studied the autocorrelation function using muon rates over a period of 932 days.[4] The period is not exactly one year, but we found the same period was present for muons and for the trigger rate.

3 Seasonal Variations in the Trigger Rate

A clear seasonal pattern in the trigger rate is evident in Figure 1. The axis is the time between triggers, or one over the trigger rate. The typical change is from 1.9s to 2.3s or a change of $\pm 10\%$. One early hypothesis was that the effect was due to electrical noise, which would be expected to greatly increase during the summer when there are many more cage rides, a greater load on the electrical system, etc. A study of the effect by time of day led to the conclusion that there is no systematic difference between day and night.

We examined some of the random triggers in detail and found that almost all of the triggers, both winter and summer, come from the outside 16 anodes. The most common cause of triggers were random hits multiplexed together into a trigger region, called "random" below. A trigger requires 7 anode edges (or 8 cathode edges). Typically, random triggers corresponded to 7 random hits from throughout the detector which were multiplexed together in one anode crate in a way which satisfied the trigger. The individual hits appeared to be real ionization (not electronic noise). The tendency to be in the first 16 anode channels means they were on the east or west side of the detector, and that the detector was attenuating the source of the hits, presumably γ rays. Thus the γ rays were predominantly coming from the rock, air or concrete, and not from inside the detector.

In caves and underground laboratories, seasonal effects in radon measurements have often been observed. Lively and Krafthefer[5] found that average winter radon concentrations in Mystery Cave Minnesota were lower than summer by at least a factor of two. Similar results were also reported from caves in Yugoslavia[6] and Hungary[7]. The cause of the differences were attributed to the airflow in the caves, which of course were locally quite different in each cave and in each part of each cave. Other literature reported other seasonal effects which may have more to do with rain and local weather patterns.[8] MACRO is in the Gran Sasso, where there is a tunnel used by automobiles, and they installed a ventilation pipe all the way to the outside. The measured radon levels were time dependent, but this depended on the quality of their ventilation with no clear seasonal effect.[9] The effects from Super-Kamiokande were much more dramatic. They found that basically radon was

absent in the Winter and present in the summer. In particular, they found levels in the summer of 1-2 pCi/liter ($=30-70 \text{ Bq}/m^3$) in the winter, but levels of 50-60 pCi/liter ($\sim 3000 \text{ Bq}/m^3$) in the summer. A recent publication shows that this radon level measured at the water pump is not affecting background levels in the water.[10]

One can imagine a simple model that must be at least partially correct. Hot air rises. In the winter, when the outside temperature is lower than the inside temperature, the air in the mine rises and there is a large rate of ventilation. There must be a circuit for air to flow, but at long as there is more than one opening to the outside, this can occur. In the summer, when the outside temperature is higher than the inside temperature, air circulation is reduced. While this simple model easily explains the Super-Kamiokande radon data, it is also easy to see how more complicated geometries lead to more complicated ventilation scenarios and reduce the effect in different caves and mines.

Radon measurements of the air in the Soudan 2 cavity have been performed by the Argonne Chemistry Division. We find levels of 3.0 pCi/liter in the winter and 13.0 pCi/liter in the summer. The anode trigger requires 7 independent hits. The random event scan verified that the 7 hits are usually independent. Thus we can estimate that the trigger rate should go as the 7th power of the change in the singles rate. The radon level varies by a factor of four, and the random part of the trigger rate varies between the summer and winter from 0.20 triggers per second to 0.14 triggers per second. This implies a change in the singles rate of 6%, since $0.14 \times (1.06^7) \sim 0.20$. Thus, radon contributes 2% of the singles rate in the winter, and 8% in the summer. As a check, singles rate have also been measured in the shield and there is a clear $\sim 6\%$ seasonal variation.

It is possible to make a rough comparison of the radon levels with the effects on the trigger rate. A 5 meter cube of air with 5 pc/L of radon will lead to about 8 electrons per square meter per second. The east and west walls of the detector have half that thickness of air between the wall and the detector, so the summer (winter) levels of 12 pC/l (3 pC/l) will result in ~ 10 (2.5) electrons/ m^2/s . Early measurements of knock-on electrons range from $40/m^2/s$ to $100/m^2/s$. Within a factor of three, the fractions of singles from radon should be 10% in the summer and 2% in the winter. This is consistent with the changes in the trigger rate.

4 Summary

There are sizable seasonal effects in the Soudan 2 data associated with cosmic rays muons ($\pm 2\%$) and with the random trigger rate ($\pm 15\%$). These effects are reproducible from year to year. The muon effect can be explained by expected temperature variations near the tropopause and their effects on the density at constant pressure. The trigger effect can be explained by seasonal effects in the radon level in the mine air. There is no reason to suspect that Dark Matter plays any role in the seasonal effects in Soudan 2.

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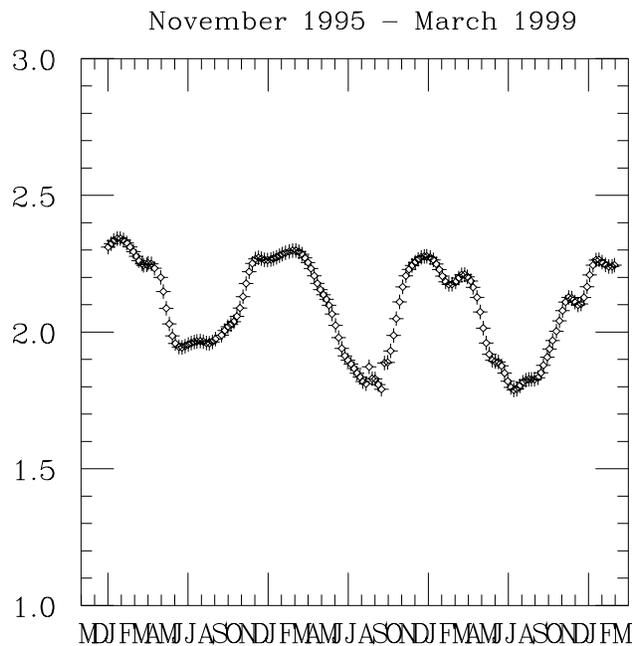


Figure 1: Trigger period (seconds) versus month in Soudan 2.