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An Experimental Search for Gamma Radiation Associated With Thunderstorm Activity*

David Fryberger

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309

I. INTRODUCTION

This experiment is a repeat of an earlier experiment,[1] but with more sensitive apparatus and in a location with a higher incidence of thunderstorm activity. The experiment of Ref. (1) was undertaken by Ashby and Whitehead (AW) to investigate the theory that ball lightning might be associated with the annihilation of small amounts of antimatter, and it yielded some very interesting but inconclusive results. In the course of about 12 months of data taking, four high rate bursts of gamma radiation were detected.[2] These events lasted a few seconds and had many thousands of counts (16500, 5000, 3700, and > 7700). Unfortunately, the association of these gamma ray bursts with thunderstorms or ball lightning was not clearly established, although one of the bursts did occur during a local thunderstorm in rough coincidence with a lightning bolt striking a flagpole[3] about 100 yards from the gamma ray detection crystals. A pulse height spectrum taken for this burst (no spectrum was taken for the other three) exhibited a significant peak, well above background, the energy of which appeared to be compatible with the 511 keV positron annihilation line. While the peak could not be unambiguously attributed to positron annihilation, this certainly appeared to be the most likely source.

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One presumes that these gamma events, should their existence be confirmed, would be clear evidence for some kind of nuclear interaction. On this point, it is interesting to note that there is some independent evidence of nuclear activity associated with the lightning discharge.[4] Of 11,200 lightning-triggered events, excess neutrons (*i.e.*, ≥ 2) were observed for 324 triggers, or 2.9 % of the triggers. This is to be compared to a measured excess neutron background rate of 1.2 % (101/8400). Moreover, the excess in lightning-triggered events over background in the multiple neutron category (≥ 3 neutrons) is far beyond any reasonable statistical fluctuation. It is conceivable that the gamma radiation of Ref. (1) and the neutrons of Ref. (4) could derive from the same physical process. That being said, however, the physics that could lead to such bursts of 511 keV gamma rays (and/or neutrons) remains unexplained. With respect to the gamma bursts, AW concluded[1] that, due to the short time duration of the bursts (a few seconds) their events were inconsistent with the (nuclear) ball lightning theory of Altschuler *et al.*[5] Based upon the results of subsequent (unpublished) data,[3] AW concluded from the lack of other nuclear radiation that their antimatter annihilation theory was not the correct explanation either. Cosmic radiation, another possible source, is ruled out by the duration of the bursts of activity and the number of gamma rays actually detected in these bursts.[6]

From the above discussion, it is clear that confirmation of the AW gamma events would be most interesting. An important additional motivation for performing the present experiment was to investigate the hypothesis that ball lightning might be comprised of a magnetic monopole plasma produced by the lightning discharge.[7] One component in the signature of this plasma would be bursts of a large number of annihilation (511 keV) gamma rays, as appear to have been detected in the AW experiment. In this theory, one would also expect the release of neutrons by ball lightning and the presence of an oscillating magnetic field. But the latter would be much more difficult to detect.

In Ref.(7), the basic physics that would lead to the production of 511 keV gamma rays (and indirectly, some neutrons) would be monopole catalyzed nucleon decay *e.g.*,

$$p + m \rightarrow e^{+} + m + n\pi,$$

where the (decaying) proton p would be locally available in the nuclei of the air molecules, and n indicates an unspecified number of pions, probably two or three. There would also be an equivalent reaction involving neutron decays. The energy released by a nucleon decaying inside a nucleus (*e.g.*, N or O) would tend to fracture the parent nucleus, ejecting a variety of low Z daughter products, including neutrons. As is the case in catalysis reactions, one notes that the monopole survives on the right hand side of the above equation, thus remaining available to trigger subsequent nucleon decays. The energetic (a few hundred MeV, say) e^{+} and gammas (from $\pi^{0} \rightarrow 2\gamma$) would generate electromagnetic showers in the atmosphere. The e^{+} in these showers would come to rest, subsequently annihilating with atmospheric electrons, yielding the 511 keV gamma radiation. In an attempt to quantify the experimental ramifications of this hypothesis, a number of EGS calculations[8] were made to estimate the range of detectability of the 511 keV signature. A result of one of these calculations is given in Fig. 1.

II. EXPERIMENTAL APPARATUS

The apparatus for this experiment was installed in KIVA II at the Langmuir Laboratory for Atmospheric Research. This KIVA is a buried Faraday cage located at an elevation of 3280 m at the top of South Baldy Peak in the Magdelena Mountains of the Cibola National Forest. At this location, the mean incidence of thunderstorms is $\sim$ 50/summer.

The electric power feeding this KIVA goes through a 7 KVA isolating transformer. The electronics racks in the KIVA are then fed through a second isolating transformer. After the second isolation transformer, the ac power then went through a UPS followed by a Waber surge protector. The racks themselves, as well

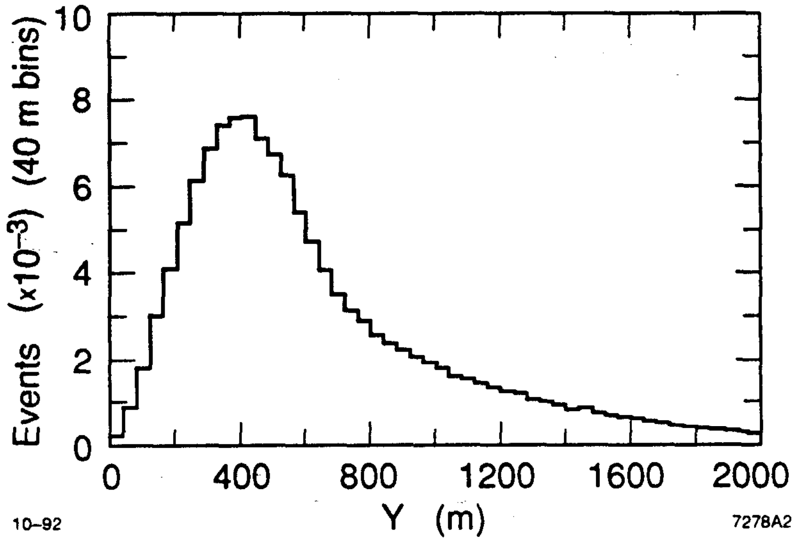

Figure 1. This EGS calculation used as input 43590 e^+ launched at $y = 0$ along the positive y-axis with an energy of 250 MeV. These e^+ caused showers, and the histogram consists of the number e^+ annihilations at rest, which total 127284, binned versus position on the y-axis. (The pair production process of the electromagnetic shower results in a final number of e^+ annihilations that exceeds the initial number of e^+'s launched.) The rate of annihilation in flight is not a major factor here; it was calculated to be ~ 15% of that at rest. Also, due to center of mass motion, the gammas from annihilations in flight would not be expected to register at 511 keV in a detector at rest in the lab frame, but rather would contribute to an increase in the level of the general background rate. It is interesting to observe that the peak of the histogram falls at ~ 400 m, consistent with the range of a 250 MeV electron in air. As expected, other calculations indicate that the peak moves to smaller y with lower initial e^+ energy and towards larger y with higher initial e^+ energy. It should be observed, however, that if one takes the $1/r^2$ range factor into account, the expected counts/event continues to rise with decreasing range until one gets well within the expected 511 keV photon range of 140 m.

as all of the experimental apparatus, were electrically insulated from the interior of the KIVA Faraday cage.

Two large NaI(Tℓ) crystals (of hexagonal cross section, 5 inches face-to-face and $16\frac{1}{4}$ inches long, each hermetically sealed in a 0.02 inch stainless steel can)[9] were used as gamma ray detectors. The crystal assemblies were mounted inside an aluminum "top hat" that was installed over a porthole in the roof of the KIVA as an integral part of the Faraday cage. The top hat was 6 feet high, 18 inches in diameter, and 0.09 inches thick. Thus, the gamma detectors were above ground level and had an unimpeded 360° exterior "view." Since the .09 inch thickness aluminum of the top hat comprises 2.5% of a radiation length, it caused no serious degradation of the gamma ray detection capability. In the course of the experiment, two triggered lightning discharges actually struck the KIVA about 3 meters from the top hat.[10] The fact that there were no anomalous electrical or electronic glitches associated with these discharges is a clear demonstration of the efficacy of the electrical shielding and filtering. It should also be mentioned here that the only power outages due to lightning were of short duration (one or two seconds). The UPS, which senses the loss of ac power in a fraction a cycle, kicked in (as advertised) and there was no impact either on the electronic apparatus or on the computer; data taking was continuous during all storms.

Each NaI crystal was viewed by a 2 inch photomultiplier tube. The PMT signal was amplified and split as shown in Fig. 2. One signal path entered a 1024 channel pulse height analyzer (a LeCroy 3001 qVt), the output of which went directly to an on-line x-y display as well as (via appropriate interfaces) to a Macintosh SE computer.

The computer, under the control of a LabVIEW program, scanned the NaI crystals every 30 s and checked whether the 511 region significantly exceeded background, which was $\sim$ 7K counts/30 s. If so, then the 30 s spectrum of that crystal was flagged, and that 30 s spectrum of each crystal was stored for subsequent analysis. Integrated spectra for the entire run (one for each crystal) were also stored at the end of each run. The run duration was optional, varying from less than an hour to several days, depending upon the weather and other activities.

The signal along the other path was amplified and fed to a T120/N discriminator; it then went through a low pass filter ($\sim$ 0.05 s time constant) to a 3-pen chart recorder. The amplifier gain and the discriminator output pulse width were adjusted so that the discriminator threshold matched the qVt threshold and the trace indicated on the chart recorder (a running average dc level) yielded a record of the real-time rate of the NaI pulses over the qVt threshold. This threshold was equiv-

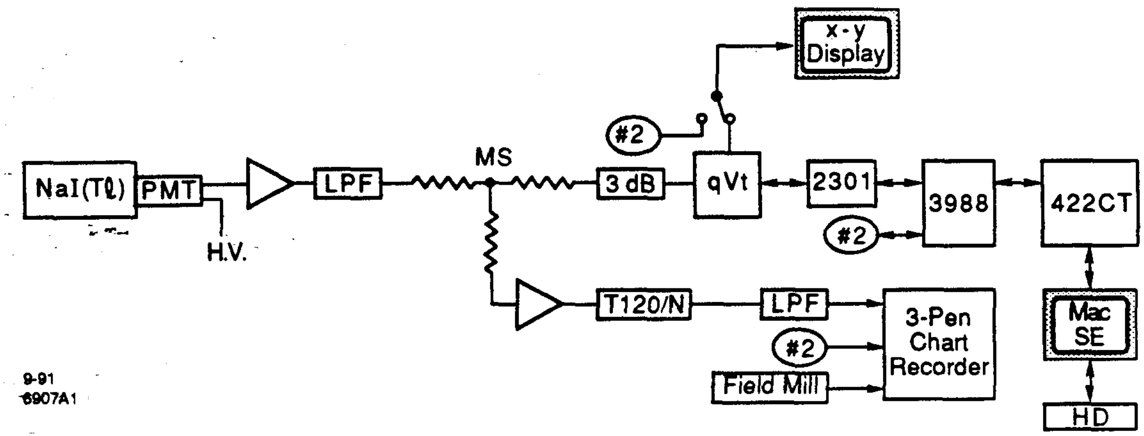

Figure 2. Experimental Apparatus. There were two NaI($T\ell$) crystals. Only one channel is depicted in the figure, the second feeding in at the points labelled #2. LPF denotes low pass filter and MS a matched splitter. Two pens of the chart recorder plotted the total rates above threshold in the two NaI($T\ell$) crystals, and the third pen plotted the total output of the field mill. The qVt's were read out via a LeCroy 2301 qVt CAMAC interface through Kinetic Systems 3988 GPIB Crate Controller and a National Instruments GPIB-422CT (IEEE 488RS-422 controller) by a LabVIEW program resident in the Macintosh SE computer. The Techtronix 604 monitor (x-y display) could be manually switched, as shown, to display the pulse height spectrum residing in either qVt. A 50 Mbyte hard disk (HD) with removable cartridges was used for data storage and program backup.

alent to about 230 keV gamma energy in the NaI crystals, and the total rate above threshold per qVt was about 1500/s. (The general background rate at 3280 m, the Langmuir elevation, was about four times that at the 100 m SLAC elevation.) The maximum analyzed gamma energy of the qVt was $\sim$ 1.9 MeV. Higher energy gammas, of course, went into the overflow bin, which was also recorded with each spectrum. Energy calibration of the NaI detectors was done using the 511 keV and 1275 keV lines of a Na^{22} source and the 1.46 MeV line of natural K^{40} in the environment. With these parameters, events such as those seen by AW would be unambiguously observed on the chart recorder trace, well above the running background.[11]

For this experiment Langmuir Laboratory furnished a field mill,[12] which was set up to measure the atmospheric electric field strength at the surface of the earth about 100 meters from the top hat gamma detectors. The electrical signal from the field mill passed through two signal conditioners to remove lightning induced transients, and then was recorded on one of the three pens of the chart recorder, as indicated in Fig. 2.

Langmuir Laboratory also made available the data from its field change meter.[13] The sensing element of this device was a disk of 12.5 cm dia. mounted under a rain shield outside the cupola of the main Langmuir Laboratory building. The voltage induced on this disk by the atmospheric electric fields was fed to an amplifier for subsequent data processing. Thus, the device was effectively ac coupled to the atmospheric electric field, measuring the displacement current associated with electromagnetic activity in the atmosphere; the decay constant of this coupling was ~ 0.03 s. Samples of the output voltage were continuously fed into a shift register at a rate of one sample per 0.455 ms. Large changes of the electric field were used to develop a trigger causing the transfer of 2000 shift register samples into permanent computer storage for subsequent analysis. Hence, the data set recorded with each trigger spanned 0.91 s. To be assured that nothing was missed prior to the trigger (*e.g.*, stepped leader activity), 25% of this data set (500 samples) was devoted to samples recorded in the shift register just prior to the initiating trigger. The remaining 1500 samples were taken following the trigger. Several gain settings were available. Triggering times were also recorded to enable time correlation with other data.

In order to monitor the location and character of the lightning discharges, Langmuir Laboratory had installed several video cameras, each viewing the KIVA II location from a different angle.[14] However, due to the frequent incidence of low cloud base at the KIVA, this technique was often ineffective. Some ranging information was possible through "flash to bang" timing, but it was not always feasible to unambiguously associate specific thunderclaps with an observed lightning discharge signal – especially during periods of high thunderstorm activity.

III. DATA

The apparatus was in place over a period of 55 days, and was actually recording data for 77% of this time (1012 hours). (In clear weather, data were generally not taken, except for some background runs; data were generally taken all night under computer control, but without an operator in the KIVA.) During this 55 days, there was a total of 29 storms, where the presence of a storm was defined as a foul weather field in excess of 5000 V/m, as registered by the field mill. Although it was difficult to obtain exact information (the KIVA had no observation port), about five of these storms passed close enough to the top of South Baldy to have had lightning discharges within 1 km of the KIVA. (Fig. 1 indicates that energetic positrons tend to range out at $\sim$ 400 m, and we note that the attenuation length of a 511-keV photon at an elevation of 3300 m is $\sim$ 140 m.)[15] During these storms, it is estimated that about a dozen discharges were within $\sim$ 500 m of the top hat detectors. In particular, five of these discharges were certifiably[16] within 100 m of the KIVA.

In analyzing the data, a candidate event was defined as a flagged 30 s spectrum in at least one of the crystals.[17] The criterion of significance for flagging and saving a spectrum was an on-line operator-specified number of standard deviations of counts in the 511 keV region above the mean number of background counts. Four sigma was a typical setting for this parameter, which implied an excess count number equal to $4\sqrt{7000} = 335$ counts. Thus, all candidates for "fittable lines" were recorded for scrutiny.[18] An event was defined as a 30 s spectrum with a "fittable" 511 keV line in coincidence with a 4 σ rate increase indicated in both of the chart recorder traces. Using only the criterion of a fittable 511 keV line above background ($\sim$ 500 counts/30 s) would lead to a detectability threshold of $\sim$ 6% of the (mean) number of counts/burst (8200) recorded by AW. However, it should be kept in mind that the detector of this experiment had an acceptance solid angle of $\sim$ 8 times[9] that of Ref. (1). Hence, the apparatus of this experiment has the capability to detect signals at a level of $\sim$ 1% of the mean detected AW events.

Including the requirement of a significant rate increase in the indicated rate on the chart recorder as part of the event criterion results in an effective "signal threshold" that is a function of signal duration, requiring a greater number of counts if the signal duration is longer than about two seconds.[19] For example, a signal burst spread out evenly over 4 s (on the order of the observed signal durations of the AW events), would need ~ 1050 counts to yield a 4 σ augmentation in the chart recorder trace, that is, a gamma ray count level of ~ 13% of the mean event count reported by AW.[1] (Again, including the larger solid angle of this experiment reduces this threshold effectively to ~ 2% of the mean of the AW events. Using this stricter criterion (both a fittable line on one 30 s spectrum and two coincident argumented chart recorder traces), the data of this experiment yielded no events. That is, there was no evidence for any excess 511 keV activity associated with the lightning discharge or with thunderstorm activity.[20] Thus, for a sample size of a dozen nearby lightning discharges, the AW results remain unconfirmed.

Radioactive washdown

It was observed that when there was extensive precipitation (> 15 min, say) at the KIVA, there was clear evidence of radioactive washdown[21]; on these occasions the general background rates in the counters increased by amounts of up to 30%. After the storm passed, this activity decayed away with a time constant of ~ 1 hr. A number of fits to the most prominent line of the washdown radioactivity were made. Typically, for the integrated data of one of these storms, a fit of a Gaussian line shape to the most prominent peak yielded a centroid located at 608.7 ± 6.6 keV with a (standard deviation) width of ~ 35 keV, consistent with the NaI resolution. The centroid value and the post storm decay lifetime of this radioactivity is consistent with the presence of the 609 keV gamma line of Bi^{214}. The existence of such radioactive washdown is well documented.[23] Its presence was also observed by AW.[1] This data also furnished an additional check on the energy calibration of the NaI crystals.

Bead Lightning

During a storm on the evening of August 9, 1991, one of the lightning discharges was visually observed (by the author and G. Hacker) to evolve into bead lightning. The discharge was east of the main laboratory building by an estimated 1 km (flash to bang). Using a topological map, this placed the discharge at a range of 2.5 km southeast of the NaI detectors at KIVA II. Unfortunately, due to its location this flash was not in the field of view of the video cameras viewing the KIVA.[24] While this discharge was clearly evident on the field mill trace, no 511 keV signal associated with this discharge was flagged for either of the NaI detectors, nor was there any discernible increase in the overall rates as recorded on the chart recorder. But it should be kept in mind that 2.5 km is beyond the detection range (of even a large burst) of 511 keV gamma rays. However, the Langmuir field change meter was taking data at the time, and the observed waveform of that discharge is included as Fig. 3. The waveform clearly exhibits a five stroke discharge (Five strokes is consistent with the flickering of the flash as observed by the author.) spanning about 100 ms followed by five surges of much longer duration. It is likely that these slow, post-flash surges are associated with a continuing current in combination with further electric breakdown in the cloud and may have some relevance to the appearance of the bead lightning. Further analysis of this event was not carried out, but this waveform is included here for the sake of general interest in the belief that it is the first electric field waveform ever recorded for bead lightning.

IV. SUMMARY and CONCLUSIONS

This experiment searched for gamma ray activity associated with thunderstorm activity. In particular, it was designed to confirm the presence of gamma ray bursts consistent in energy with the 511 keV line associated with e^+e^- annihilation, as reported by Ashby and Whitehead.[1] In the course of the data taking, an estimated twelve lightning discharges took place within a range of 500 m from the gamma ray detectors.

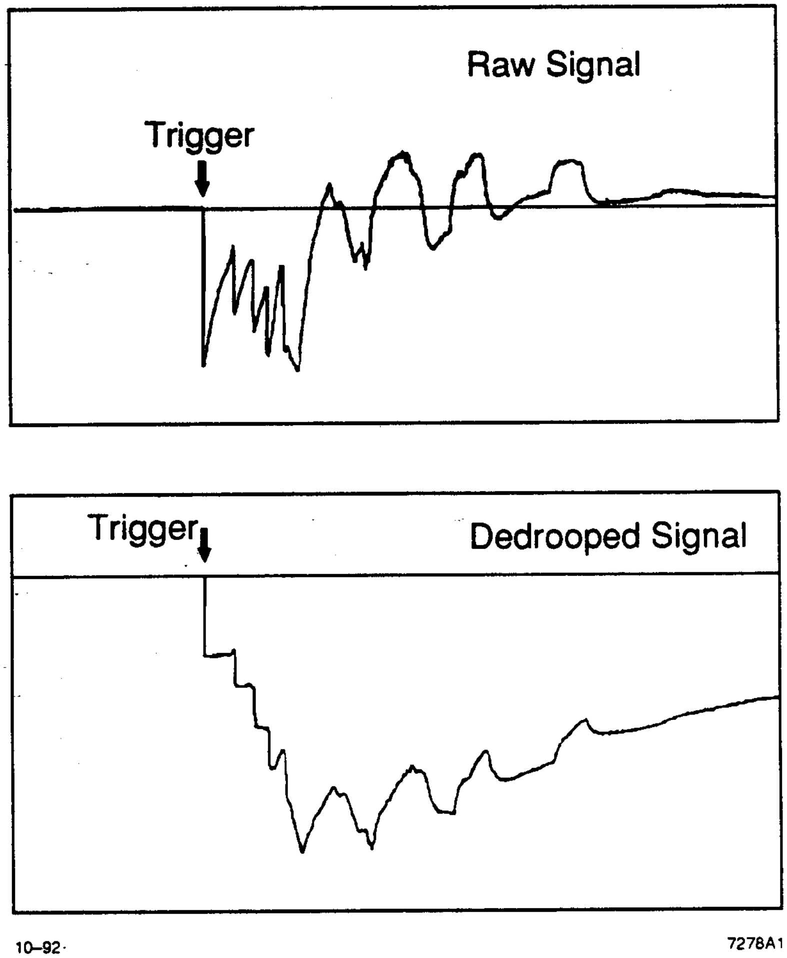

Figure 3. Bead lightning waveform. One can see that this flash is comprised of five strokes. As described in the text, one fourth of the data in this trace comes prior to the first stroke. The upper trace is the amplified output. The exponential decay after each stroke, due to the (effective) ac coupling of the amplifier to the atmospheric electric field is clearly in evidence. The lower trace is the same data after a computer process called "dedrooping," which removes the instrumental convolution effects of the ac coupling.

No evidence for such 511 keV gamma ray bursts was observed at a "signal level" a factor of ~ 50 below the mean count level of the events of Ashby and Whitehead. Hence, one concludes that the probability of such events must be $\leq 10\%$ per lightning discharge. While this result may seem inconclusive, it does at least furnish a proof that such gamma radiation is not a common feature of the lightning discharge. Unfortunately, the present experiment did not have enough nearby lightning discharges to examine the probability of 511 keV gamma events at the 2% level (per lightning discharge), which would enable a comparison to the neutron data.[4] Hence, this result, through negative, is not inconsistent with the positive indication of lightning induced neutron events. To resolve this question, an experimental study, preferably in conjunction with neutron detection, of a larger data sample would be needed.

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REFERENCES and NOTES

1. D. E. T. F. Ashby and C. Whitehead, *Nature*, **230**, 180 (1971).

2. Ref. (1) employed two gamma ray detectors: one 900 cm^3 NaI crystal and one 20 cm^3 lithium drifted germanium crystal.

3. D. E. T. F. Ashby, Private Communication.

4. G. N. Shah, H. Razdan, C. L. Bhat, and Q. M. Ali, *Nature*, **313**, 773 (1985).

5. A secondary motivation for the Ashby and Whitehead experiment was to investigate the idea that ball lightning might be a nuclear phenomenon, as suggested by M. D. Altschuler, L. L. House, and E. Hildner, *Nature*, **228**, 545 (1970).

6. S. Cecchini, G. Di Cocco, and N. Mandolesi, *Nature*, **250**, 637 (1974).

7. D. Fryberger, in preparation. This ball lightning hypothesis is based upon the physics of a specific electromagnetic monopole configuration called the vorton. The vorton and its structure are described by D. Fryberger, *Hadronic Journal*, **5**, 1884 (1981).

8. The acronym EGS stands for Electron Gamma Showers. The code for calculating these showers is fully described by W. R. Nelson, H. Hirayama, and D. W. O. Rogers, *The EGS4 Code System*, SLAC Report 265 (1985).

9. Thus, the NaI(Tℓ) crystals each have a volume of 5765 cm^3 – giving a volume factor of $6.4 \times 2 = 12.8$ (totalling both crystals) over that of Ref. (1). Using a mean cross sectional area (calculated by averaging over the hemisphere of possible source directions) as the more relevant parameter, one estimates that the solid angle (again adding both crystals) for the detection of gamma radiation of this experiment is roughly eight times that of Ref. (1).

10. The triggered lightning project was carried out by B. Hibbs; his rocket launching apparatus was mounted on the plate that formed the top or roof

of the KIVA. The decision to launch was based on the field mill voltage.[13] The actual launch trigger was pneumatically actuated from inside the KIVA.

11. The chart recorder gain was adjusted so an average count rate of 1000 counts/s would yield a pen displacement of 0.5 inch. The mechanical linkage of the chart recorder was the frequency response limit. The effective output rate of the pen trace is three (independent) samples per second, which implies about 500 counts/sample when recording the background ($\sim$ 1500 counts/s and a mean pen displacement of 0.75 inches). For each chart recorder sample, then, one sigma equals $\sqrt{500} \cong 22$ counts. An event that would augment the general background rate by 1000 counts/s (or 330 counts/sample) would be a 15σ effect in each augmented sample ($\sim$ one half an inch on the chart recorder trace - easily visible above the normal statistical fluctuations).

12. The calibration factor of the field mill was 9300 V/m for each volt of output. The fair weather field is defined as negative (electric gradient pointing downward), and the foul weather field is defined as positive (electric gradient pointing up). Operation of the field mill was verified daily using a charged (by rubbing with a cloth) teflon rod.

13. W. Rison, S. Hunyady, and C. B. Moore. In preparation.

14. The primary mission of these video cameras was a Langmuir Laboratory experiment to evaluate a certain type of lightning arrester. but the Laboratory kindly made the video recordings available as possible supplementary data for this experiment.

15. This estimate, which is derived from the Photon Attenuation Length Graphs, Particle Data Group, *Phys. Rev. D*, **45, Part II**, III.21 (1992) also takes into account the reduced atmosphere density (72%) at 3300 m.

16. Of these, two were the triggered lightning discharges which hit the KIVA (A third rocket launch failed to trigger a lightning discharge.); one hit a lightning arrester located $\sim$ 20 m to the east of the top hat; one hit a tree at $\sim$ 100 m

range at an azimuth of $\sim 70°$; and the fifth appeared (by video observation) to have struck South Baldy southwest of the top hat at a range < 100 m.

17. It is possible that an event could occur while one of the qVt's was being scanned. In this case, only one of the 30 s stored qVt data sets would register an increased gamma ray rate; the qVt being scanned is turned off during the scanning process. The scan time for a qVt is ~ 3 s, yielding a dead time of $\sim 10\%$ in each qVt for the 30 s data collecting period. The qVt's were scanned one at a time; hence, one qVt was always actively taking data. (The data going into both chart recorder traces was always active, since these followed a path parallel to the qVt's and hence were independent of the state of the qVt's.) Also, since the qVt scans were done in direct sequence, the data sets in the two qVt's had $\sim 90\%$ overlap in real-time. Hence, it would be likely (but not assured) that a putative (flagged) event would appear in both of the 30 s stored qVt data sets.

18. "Fittable line" means that the signal was large enough to yield a fittable 511 keV line shape above a 30 s background spectrum. By taking simulated 511 keV data samples with a Na^{22} source, it was determined that the "minimum detectable signal" in the form of a fittable 511 keV line on top of a 30 s background spectrum was on the order of 500 counts. A fittable line could not be discerned with < 400 counts in the spectral line. When there were > 500 counts in the spectral line, fittability was unambiguous, improving rapidly as the number of counts in the line was increased. Thus, taking $1\sigma = \sqrt{7000} = 84$ counts, an excess of 500 counts amounts to a 6 σ effect, well beyond a simple 4 σ statistical criterion.

19. Typically (in order not to be inundated with paper), the chart recorder was not run at a speed sufficiently high (≥ 60 mm/min) to enable a short sequence of samples to be independenly discerned in the recorder trace. Thus, as discussed in the text, requiring a significant bump in the chart recorder trace as part of the event criterion tended to raise the event detectability

threshold for events whose counts would be spread out over a period exceeding ~ 2 s.

20. The number of candidate events associated with flagged 30 s spectra was consistent with the number expected from Poisson statistics.

21. The initial source of this radioactivity is the natural U^{238} in the ground, which exhales Rn^{222} into the atmosphere.[22] Subsequently, in the atmosphere the decay chain $Po^{218} \rightarrow \alpha + Pb^{214}$, $Pb^{214} \rightarrow \beta^- + Bi^{214}$ takes place, where Po^{218}, Pb^{214} the Bi^{214} have half lives of 3.0 m, 26.8 m and 19.3 m, respectively. These three elements are washed down by the rain. There is also a small contribution to radioactive washdown from the daughter products of Th^{232}.

22. C. E. Junge, *Air Chemistry and Radioactivity*, (Academic Press. NY, 1963), Chap. 3.

23. A. Katase, Y. Narahara, Y. Ishihara, K. Tanoka, and H. Matsuyama. *Jour. Nucl. Sci. and Tech.* (Japan), **19**, 918 (1982).

24. The flash was recorded in the whole sky video camera. Unfortunately the resolution of this instrument was inadequate to reveal any information on the beading of the discharge.