Fair Weather Neutron Bursts from photonuclear reactions by Extensive Air Shower core interactions in the ground and implications for Terrestrial Gamma-ray Flash signatures

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Key Points:

- We report on fairweather count rate bursts with 2ms duration following the impact of a large cosmic ray shower near a small scintillation detector at HAWC.
- Simulations show that the spectra and decay time can be produced by either hadronic interactions, or photoneutron reactions from gamma-rays.
- These results imply that downward TGFs could produce a similiar delayed neutron signature in the soil near ground based detectors.

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Abstract

We report on anomalously long duration (2 ms) count rate bursts following the impact of cosmic ray showers near a 7.62 cm x⌀7.62 cm $LaBr_3$ scintillation detector at the High Altitude Water Cherenkov array in Mexico, previously described by Stenkin et al., 2001, and termed 'neutron bursts'. The largest burst produced 198 counts within 2ms in our $LaBr_3$ detector. We simulate the neutron burst albedo flux (that is, secondary emissions from an extensive air shower core impacting the ground), and show that 1.) the characteristic spectra and count rates are well explained by neutron absorption in the ground and 2.) any cosmic ray secondary that produces neutrons, either through hadron inelastic collisions, or photoneutron production by gamma-rays, produces the same characteristic spectra. This implies that other natural phenomena that produce downward beams of gamma-rays, like Terrestrial gamma-ray flashes, should produce a similar 'neutron burst' signature from the photoneutron reactions occuring in the soil.

1 Cosmic Ray Showers

A cosmic ray-induced air shower is a particle cascade initiated at the top of the atmosphere by an incident primary cosmic ray whose angle with respect to zenith, θ, defines the shower axis. The cascading secondary particles form a pancake shaped front of particles normal to the shower axis that moves forward close to the speed of light. An air shower is typically composed of a hadronic core that continuously feeds electromagnetic and muonic particles laterally away from the shower axis as the shower travels downwards (Ziegler, 1998). For air showers initiated by cosmic rays near 10^{15} eV, the pancake can have a diameter, D, of 100 m, and a thickness, ΔL of 1 to 2 m by the time it reaches the ground (Gaisser et al., 2016). As a consequence of this geometry, all particles within the thickness of a small area on the pancake (order ΔL^2) will arrive at the ground within a very short time ($\Delta L/c \approx 3$ ns for a 1 m pancake thickness) as compared to the delay between the arrival of particles located at different ends of the pancake ($D/(c \sin\theta) \approx 500$ ns for a 100 m diameter pancake arriving along $\theta = 45°$). By treating the pancake as a wavefront, large spatially distributed particle detector arrays (with dimensions on the order of the air shower footprint) like the High Altitude Water Cherenkov Array (HAWC) (Abeysekara et al., 2012), and the Large High Altitude Air Shower Observatory (LHAASO) (Bai et al., 2019) can infer the direction of the primary cosmic ray by tracking the time it takes the pancake to sweep across the array, and its energy by measuring the size and energy deposited by the footprint of the air shower that falls onto the array.

2 Neutron Bursts, or Cosmic Ray Shower Ground Interaction Albedo

From this simple picture, it is expected that a small, fast scintillator detector will observe the passage of an extended air shower as a single, piled-up pulse, or count (small means on the order of a few square meters, and fast means a scintillation decay time of 25-100 ns). However, an anomalously delayed phenomenon that produces many discrete counts observed up to several milliseconds following the passage of large air showers has been observed at neutron monitor observatories (Aushev et al., 1997; V. A. Antonova et al., 1999; V. P. Antonova et al., 2002) and other EAS arrays (Jędrzejczak et al., 2006; Shepetov et al., 2020) . This delay is too long to be explained by statistical fluctuations in the longitudinal development of the air shower, which is on the order of 10s of nanoseconds (Agnetta et al., 1997), nor by spurious pulses produced by the PMT, such as afterpulsing, luminous reactions, and ionization of the residual gases, which can produce spurious pulses on the order of 10 ns - 10 μs after primary pulses (Photonis, 2002; Abbasi et al., 2010). One hypothesis was that the delayed signal could be from the late arrival of non-relativistic (or 'sub-luminal') neutrons evaporated from air-nuclei following the passage of the air shower through the atmosphere, termed 'neutron thunder', but this can only explain delays on the order of 10s of microseconds, and cannot reproduce the observed exponential time distribution of delayed counts (Ambrosio et al., 1999). Stenkin et. al. termed these bursts of anomalously delayed counts 'neutron bursts', and showed that the delayed timescale and exponential distribution of their arrival times were consistent with evaporation neutrons created in the ground near the detector at the point of the cosmic ray shower core impact (Stenkin et al., 2001; Stenkin & Valdés-Galicia, 2002). The basic neutron burst mechanism is currently understood to be as follows:

1. a hadronic core of a cosmic ray shower produces many high energy evaporation neutrons in the ground near the detector;
2. these energetic neutrons thermalize and are absorbed over a timescale which depends on the composition of the ground;
3. these neutrons are captured in nuclei and produce high energy gamma-rays through (n, γ) reactions;
4. the anomalously delayed counts are due to these neutron capture gammas and their scattering products.

3 Neutron Burst observations at HAWC

Neutron bursts have recently been observed at HAWC at an altitude of 4.1 km in a 7.62x⊘7.62 cm $LaBr_3$ scintillation detector attached to a spare data channel of the Broadband Interferometric Mapping and Polarization (BIMAP) sensor recently deployed to HAWC (Shao et al., 2018). BIMAP is an array of three broadband RF antennas, each consisting of two orthogonal linearly polarized dipoles with a bandwidth of 20-80 MHz. They are located north of the main HAWC water cherenkov detector (WCD) array shown in figure 1. The $LaBr_3$ scintillation detector is located in a small Pelican brand transport case sitting outside on the ground, and calibrated to bright spectral features of its internal radioactivity, namely the prominent 1436 keV gamma + 32 keV x-ray peak from the decay of $^{138}_{57}$La.

The $LaBr_3$ detector is an 38S38 St. Gobain BrilLanCe380, connected to an Ortec Scintipak supplying 800 V to the detector PMT. The base PMT output is sampled at 190 MSPS when the BIMAP system is triggered. BIMAP is programmed to trigger when either the RF power on any antenna exceeds a certain threshold, or when the integrated $LaBr_3$ PMT pulse exceeds a certain level. For each trigger, BIMAP captures 15 ms of data with 5 ms pre-trigger data. The fairweather background in the $LaBr_3$ at HAWC is ∼0.45 counts/ms, and whose spectra is dominated by the typical intrinsic background spectra of LaBr3 shown in figure 11 of (*Saint Gobain Technical Note*, 2019).

An example of the largest neutron burst observed between September 2017 and September 2019 is shown in figure 2. The large pulse at t=0 corresponds to a saturated pulse in our detector and is associated with the passage of the cosmic ray shower pancake shown in figure 1.

Following the recovery of this large PMT pulse, there is a series of 198 counts from 6 μs after the initial rising edge of the saturated pulse out to 2 ms post-trigger. We subtract off the falling baseline of the saturated pulse using a median filter window, and show the integrated pulse-height spectrum off these 198 counts in figure 2b. There is a notable peak near 511 keV. The count rate of these pulses in figure 2c follows an exponential fall-off with an e-folding time constant of 500 ± 50 μ s, as shown in figure 2c.

We estimate that the pulse height out of our PMT saturates for energy deposits larger than ∼8 MeV. We observe many of these 'saturated' pulses within a given

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Figure 1. The 300 water cherenkov detectors (WCD) comprising the main HAWC array. Each WCD contains four PMTs. In this figure, the color indicates the arrival time at the tank of a cosmic-ray shower wavefront, and the size of the colored circle indicates roughly the energy deposited in the tank. The three antennas comprising the Broadband Interferometric Mapping and Polarization (BIMAP) instrument (colored diamonds) and the approximate location of the $LaBr_3$ detector (red cross) are indicated. The X-axis is along East-West, and Y-axis is North-South.

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Figure 2. Neutron burst observed by a 7.62 cm x⊘7.62 cm $LaBr_3$ scintillation detector on 2018/08/13. (A) ∼180 MHz sampled output from PMT coupled to the 7.62 cm x⊘7.62 cm $LaBr_3$ scintillation crystal. The large spike at t=0 corresponds to passage of cosmic ray shower (CRS). Subsequent pulses out to ≈ 2 ms correspond to particle interactions in the detector. (B) Energy spectrum of pulses from baseline-subtracted detector output waveform. There is notable peak near 511 keV. (C) Count rate of pulses after passage of cosmic ray shower at t=0. The Red line shows an exponential fit to the count rate, with a time constant of 500 ± 50 μs . (D, E) Detail of RF signals recorded by the BIMAP system during the passage of the CRS. (D) Interferometry can be used on the waveforms from antennas, A_0, A_1, and A_2 to provide a direction of the RF signal. (E) The signal from A_0 provides polarization (along East-West, or North-South). The black line shows the falling edge of the $LaBr_3$ PMT output, indicating the arrival of the CRS at the ground.

			BIMAP		HAWC		
Time [UTC]	counts/2ms	τ [μs]	θ [°]	ϕ [°]	θ [°]	ϕ [°]	Precip [in]
2018-08-13/08:49:58.08860739*	198	500 $\pm$ 50	30	100	33	96.7	0.4 (0.4)
2018-08-05/06:36:28.60623834	79	536 $\pm$ 98	-	-	36.4	21.1	0.4 (0.8)
2018-10-06/07:12:54.97530532	40	925 $\pm$ 436	-	-	24.9	101.7	0.0 (0.1)
2018-07-29/08:42:03.15699945	45	754 $\pm$ 275	-	-	45.4	159.8	0.0 (0.2)
2018-06-05/07:36:25.40472688	45	731 $\pm$ 203	-	-	27.3	147.3	0.0 (0.0)
2018-12-23/11:36:08.79933614	33	1886 $\pm$ 1445	-	-	43.6	54.3	0.0 (0.0)
2019-05-16/18:19:49.49149813	56	583 $\pm$ 138	30	40	29	49	0.1 (0.5)

Table 1. The brightest neutron bursts observed at HAWC by a 7.62 cm x⌀7.62 cm $LaBr_3$ scintillation detector between Sept 2017 and Sept 2019. 'Counts' is the total number of counts within a 2 ms interval, >50 keV, recorded in the $LaBr_3$ detector, starting at 6 μs after the impact of a large cosmic ray shower observed by HAWC. 'τ' is the time constant fit to the count rate using an exponential fall off. θ and ϕ are the zenith and azimuth angle of the cosmic ray shower reconstructed from HAWC and the Broadband Interferometric Mapping and Polarization Instrument (when possible). 'Precip' shows the recorded precipitation the day of and previous day (in parenthesis) as reported by `https://www.meteoblue.com/en/weather/historyclimate/weatherarchive/18.995N-97.308E`. *See figure 1 & 2.

day, likely the minimum ionizing energy deposits from typical background cosmic ray muons, but they are typically not followed by any significant delayed counts after t=0.

From the timing of the pancake wavefront sweeping over the array, the direction of this shower was determined to be from a zenith angle θ of 30 degrees, and an azimuth angle ϕ of 100 degrees counter clockwise from east. Because the footprint of this pancake exceeds the size of the HAWC array (as did all showers observed coincident with the neutron bursts listed in table 1.), the primary energy could not be determined (further work is needed to constrain the lower energy limit of these showers using the array reconstruction), the shower's impact location could not be determined, and the nature of the air-shower (gamma-generated vs hadron-generated) could not be determined.

Coincident with the arrival of the cosmic ray shower at the array, BIMAP detected an impulsive, linearly polarized (along east-west) RF pulse, associated to a source in the sky with the same zenith and azimuth as determined by HAWC for the cosmic ray shower figure 2d,e. Large cosmic ray showers (with energy above 10^{16} eV) are expected to produce detectable RF signals, with mainly east-west polarization due to the deflection of the positrons and electrons in the Earth's magnetic field and other effects (Huege, 2016).

Neutron bursts at HAWC were discovered by searching the $LaBr_3$ records for large count rate events (> 30 counts within 2 ms). In Table 1 we list the 7 brightest neutron bursts observed at HAWC by the $LaBr_3$ scintillation detector between Sept 2017 and Sept 2019. For every instance where the $LaBr_3$ observed a large spike followed by a significant number of delayed counts, HAWC observed a large cosmic ray shower whose footprint exceeded the size of the array.

All of these events occured during fair-weather days, meaning that there was no nearby thunderstorm activity.

In addition to the 7 bright events discussed here, there was found to be a continuum of 'fainter' events (meaning less than 30 counts within 2 ms observed in the $LaBr_3$), which will be the subject of future work.

4 Neutron burst spectra compared to simulated CRS Albedo Flux

For this work we simulate the albedo gamma-ray flux from a cosmic ray shower and compare to our $LaBr_3$ observations. In the first stage we use `CORSIKA` (Heck et al., 1998) (v.7.6400, QGSJET for high-energy hadrons, GHEISHA for low energy hadrons, and EGS4 for the electromagnetic component) to simulate the flux of air shower particles that arrive at 4.1 km from a 10^{17} eV cosmic-ray proton entering the top of the atmosphere at vertical incidence ($\theta = 0$), with a magnetic field set to the field value at the HAWC site, e.g. 27.717 μT North and 29.907 μT downwards. We choose 10^{17} eV TeV as the primary energy to be sufficiently large so as to produce a detectable RF signal (as was observed). We track the particle types ($\gamma, e^{\pm}, n, p, \mu^{\pm}, \pi^{\pm}$, etc), their momentum, and radial offset from shower nadir. For γs, and $e^{\pm}$s, we track energies down to 10 MeV. For hadrons (n, p, $\pi^{\pm}$), `CORSIKA` only tracks energy down to 50 MeV. We assume all air shower particles arrive at the ground at time t=0. In the second stage, we use `GEANT4` (Agostinelli et al., 2003; Allison et al., 2006, 2016) (v.10.04.p02, using FTFP_BERT_HP_LIV) to throw these secondary particles into a mass model of the ground, being SiO_2 with a density of 2 g/cm^3, and record the flux of gamma-rays (their energy and radial offset from nadir) emitted from the surface of the ground starting from 6 μs after shower impact. We term the gamma-rays produced by this process the gamma-ray albedo flux. We note that `GEANT4` does not model particle interactions above 100 TeV. For this work, any secondary shower particles from the `CORSIKA` simulation above 100 TeV are simply thrown as a particle with energy 99.9 TeV. The average and individual spectra of albedo gammas and their count rates within a 1 meter diameter of the shower impact from 10 simulations are shown in figure 3, and are compared to the 7 brightest neutron bursts observed at HAWC between 2017 to 2019. This model simulation is consistent with recent observations by (Shepetov et al., 2020) who found that excess neutron flux typically required the impact of large showers ($E_0 > 10^{16}$ eV) within close proximiaty of the detectors ($r <$ 5 - 10 m).

We note that there is qualitative agreement between the observed $LaBr_3$ spectra and the simulated gamma-ray albedo flux from a cosmic ray shower, notably the prominent peak at 511 keV. While we do not simulate the $LaBr_3$ detector response, assuming an effective area equal to the geometric area of the $LaBr_3$ crystal, $A_{\rm eff}$ = 60cm^2, the expected number of counts from our simulated albedo flux, ϕ_γ, is $A_{\rm eff}\phi_\gamma$, and is comparable in magnitude to the observed spectra (@ 500 keV, 8 counts observed vs 4.2 simulated). In addition, there is qualitatively good agreement between the observed $LaBr_3$ count rate time distribution and the simulated gamma-ray flux time distribution, namely, each exhibits a falling exponential distribution characterized by a similar e-folding time. As discussed in (Stenkin et al., 2001; Stenkin, Djappuev, & Valdés-Galicia, 2007; Stenkin, Volchenko, et al., 2007), this e-folding time is expected to be related to the rate of neutron absorption, which in soil can be calculated as $\tau_{\rm SiO_2} = \lambda_{abs}/v_t$, where v_t is the thermal neutron speed $\approx$ 2200 m/s, and λ_{abs} is the mean free path for absorption. In pure soil with ρ = 2 g/cm^3, $\lambda_{abs} \approx$ 2.5 m, and $\tau_{\rm SiO_2} \approx$ 1.1 ms. This time constant can be reduced by decreasing the mean free path for neutron absorption, which can be done by either increasing the density of the soil, or adding water content. For pure soil with ρ = 5 g/cm^3, the time constant becomes 488 μs (but this is an unreasonably high density for soil). For soil with ρ = 2 g/cm^3 and 6% water content by weight, the time constant is 661 μs (figure 3d), consistent with an observed time constant of 500 μs. In 1 we list the recorded precipitation on the day of and previous day of neutron burst observation, and note that there is generally

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Figure 3. (A) Observed Spectra and (B) Count rate of the 7 brightest neutron bursts that occurred at HAWC between 2017 to 2019. Black histograms show brightest neutron burst event on 180813. Red histograms show averages of 6 next brightest events, shown individually by grey lines. (C) Simulated Spectra and (D) Count rates of albedo gammas ($>$ 50 keV, and occurring $>$ 6 μs after CRS ground impact) resulting from the development of a 10^{17} eV proton air shower at 4.1 km input into a ground of SiO_2. 5 individual runs are indicated by black lines, their average is indicated in red.

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Figure 4. (Left) Spectra of secondaries in an air shower at 4.1 km produced from a $10^{17} eV$ vertically incident proton at the top of the atmosphere. Vertical dashed line indicates `CORSIKA`'s 50 MeV cutoff for tracking hadrons. (Right) The average contribution of each air shower secondary species at 4.1 km to the flux of albedo gammas ($>$ 50 keV, occurring $>$ 6 μs after CRS ground impact, within 0.5 m of nadir) from ten vertically incident 10^{17} eV proton air showers.

a trend of smaller time constants associated with more rain the day before, consistent with the model above.

5 Discussion

It is perhaps suprising that only 2 of the 7 strongest neutron burst events were accompanined by a detectable RF signature in BIMAP, as the diameter of the RF footprint for high signal amplitudes (associated with near-vertical showers) is on the order of 100-200 m, and for lower signal amplitudes (associated with zenith angles near 50°) is up to 1000 m (Huege, 2018). The seperation between the $LaBr_3$ detector and the closest BIMAP antenna (A0) is 19m. It may be that the shower energy threshold for producing observerable neutron bursts in our small scintillator is below the threshold for detectble RF, or that there are different combinations of impact geometry that will produce observable neutron bursts and no RF, or vice versa.

The simulations we have presented are fairly rough (for example, it is undesirable that `CORSIKA` only tracks hadrons down to above 50 MeV (recent TGF simulation work by Ortega (Ortega, 2020) has used FLUKA to model hadrons down to 100 keV), we did not simulate the shower at the observed zenith angle for our brightest event, nor over a spectra of primary energies, and `GEANT4` is not suited to handling particles above 100 TeV), but we can still make some significant fundamental observations from these results.

The prominent spectral feature in the observation and simulations near 0.5 MeV is a 511 keV positron-annihilation line. These positrons arise from pair production of high-energy gamma quanta produced in the neutron-capture (n,γ) reactions. For example, in the cascade of nuclear gamma-ray emissions resulting from the ^{28}Si(n,γ)^{29}Si reaction, the most likely emissions are 3.5 MeV and 4.9 MeV gammas, and the ratio of the cross sections for pair production and Compton scattering in soil at these energies is approximately 0.1. This means that 10% of n-cap gamma interactions in the soil will produce a positron that will annihilate to give a 511 keV gamma.

In figure 4, we show the total spectra of secondaries in the air shower at 4.1 km produced by a vertically incident 10^{17} eV proton in the atmosphere (figure 4a), and the contribution each secondary species makes to the total gamma-ray albedo flux (Figure 4b). Figure 4b shows that the characteristic gamma-ray albedo spectrum is largely independent of the incident secondary particle species into the ground. The reason is that the spectrum is due to neutrons, which can be produced through either hadronic interactions from hadrons, or photoneutron reactions from gammas. For our simulation, the most dominant contribution to the neutron burst spectra is from secondary gamma-rays, and as far as we know, this is the first time that photoneutron production in the ground has been considered in modeling neutron bursts, with previous work only considering hadronic interactions (Stenkin & Valdés-Galicia, 2002; Stenkin, Djappuev, & Valdés-Galicia, 2007).

6 Conclusions

(1) We present the first spectrum of a cosmic ray neutron burst, observed at HAWC, and show that neutron burst spectrum and decay rates are consistent with reactions associated with thermal neutron absorption reactions in the ground.

(2) From our rough simulations, we show that the characteristic neutron burst albedo spectra and count rate are independent of the secondary particle species impacting the ground, as long as the particle type is effective at making neutrons, either through direct hadronic interactions in the soil, or photoneutron production in the soil from gamma-rays through the (γ, n) reaction. This means that the signature of neutron bursts should be expected from any large cosmic ray shower that has a sufficiently large electromagnetic component, even 'coreless' showers (Stenkin, 2003) at lower altitudes.

(3) A detectable RF signal with mainly east-west polarization was associated with the largest neutron burst observed, which produced 198 counts over 2 ms in our 7.62x⊘7.62 cm $LaBr_3$ scintillation detector, as well as a smaller burst, which produced 56 counts over the same time interval. RF signals associated with Cosmic Ray Showers were first observed in 1965 (Askar'yan, 1965), with many groups continuing these observations today (Ardouin et al., 2005; Fliescher & Pierre Auger Collaboration, 2012; Schellart et al., 2014; Scholten et al., 2016; Bezyazeekov et al., 2015; Aab et al., 2016b, 2016a; Shao et al., 2018). This work highlights the liklihood that observations of strong cosmic ray RF signals may indicate the presence of nearby neutron bursts. This with conclusion 2

also imples that a combination of small radiation detectors and sensitive RF receivers (like BIMAP) used for terrestrial gamma-ray flash (TGF) observations may be able to detect and study the passage of high energy cosmic ray showers ($>10^{16}$ eV).

(4) This work suggests that TGFs could produce a detectable 'neutron burst' if the TGF occurs near the ground. If detected, TGF-related neutron bursts may provide a temporally distinct, but similar neutron signature in detectors searching for thunderstorm neutrons (Babich, 2019). For example, a downward TGF produces 3 distinct detector signatures: 1.) The arrival of the TGF gammas, with a duration of $\approx 100\ \mu$s (Hare et al., 2016); 2.) The neutron afterglow, resulting from the arrival of sub-luminal photoneutrons produced by TGF gammas in the atmosphere, with a duration of ≈ 100 ms (Bowers et al., 2017); 3.) the positron glow from the radioactive decay of photoneutron products in the atmosphere, lasting several seconds (Rutjes et al., 2017; Enoto et al., 2017). A neutron burst resulting from the TGF gammas incident on ground near a TGF detector would have a duration of a few milliseconds, and have spectral characteristics similar to the TGF neutron afterglow.

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