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Origin of neutron flux increases observed in correlation with lightning

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[1] The past decade of research into the phenomenon of lightning has seen an accumulation of evidence for the existence of penetrating radiation (X- and γ-rays) in direct association with many forms of discharges. As a result, our basic understanding of the mechanisms that produce lightning has shifted from the present paradigm based on conventional breakdown to a picture that incorporates the acceleration and avalanche of energetic particles. Experiments conducted at high mountainous facilities in Gulmarg, India, have further confirmed the need for a paradigm shift. These measurements have shown an enhancement in neutron flux in the atmosphere in correlation with lightning electromagnetic pulses. We demonstrate here that the prevailing neutron generation theory based on synthesis of deuterium nuclei in the lightning channel is not feasible. Instead, this phenomenon is most likely connected with photonuclear reactions produced as part of the recently elaborated theory of relativistic runaway breakdown.

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1. Introduction

[2] The significance of neutron production by lightning was noted by *Fleischer et al.* [1974] (hereinafter referred to as FPC). Not only does the generation of neutrons provide valuable information about the discharge mechanism itself but an enhanced neutron flux would also have important consequences for ^{14}C dating through the neutron capture reaction n(^{14}N, ^{14}C)^{1}H. The implications of the latter are that the ages of various materials would be underestimated unless the historical occurrence rate and geographical distribution of lightning were taken into consideration. FPC also point out that long-term variations in the neutron flux would affect the reliability of fission track dating and consequently any fission decay constants that were inferred from those radiological measurements.

[3] Until recently, the basic discharge mechanism of lightning was thought to be well understood and was rooted entirely in the conventional breakdown observed in the laboratory [*Coroniti*, 1965; *Golde*, 1981; *Loeb*, 1939; *MacGorman and Rust*, 1998; *Raizer*, 1991; *Rakov and Uman*, 2003; *Uman*, 1969, 1987]. The past several decades of research into the phenomenon of lightning, however, has seen an accumulation of evidence for the existence of penetrating radiation (X- and γ-rays) in direct association with many forms of the lightning discharge [*Dwyer et al.*, 2003; *Eack et al.*, 1996; *Fishman et al.*, 1994; *McCarthy and Parks*, 1992; *McCarthy and Parks*, 1985; *Moore et al.*, 2001; *Smith et al.*, 2005]. A historical review of the experiments conducted since the early 1930s in search of penetrating emissions from thunderstorms is given by *Babich* [2003] and *Suszcynsky et al.* [1996]. A possible explanation for the prevalence of these energetic processes in lightning lies with the theoretical ideas first advanced by CTR Wilson, who speculated on the ability of "strong electric fields such as those of thunderclouds" to accelerate charged particles to very high energies in the dense lower layers of the atmosphere [*Wilson*, 1924]. However, subsequent searches for evidence to support these ideas led to conflicting results [*Suszcynsky et al.*, 1996], and it was not until the measurements of *McCarthy and Parks* [1992, 1985] that confirmation of CTR Wilson's hypotheses began to take root. In 1992 *Gurevich et al.* [1992] described how a relativistic avalanche mechanism that they termed relativistic runaway breakdown would work in the electric field of a thunderstorm and it became clear that the lightning discharge could take on an entirely different character than previously envisioned [*Dwyer*, 2005]. Subsequent theoretical and observational work has supported the notion that relativistic runaway breakdown plays a significant role in the lightning process. As will be shown in this paper the measurements of enhanced neutron fluxes in association with lightning can only serve to further confirm this notion.

[4] The first evaluations of neutron yield from lightning were obtained by scaling the reaction ^{2}H(^{2}H, n)^{3}He in electrical explosions of nylon threads enriched by deuterium [*Libby and Lukens*, 1973; *Stephanakis et al.*, 1972]. On the basis of their results it was *Libby and Lukens* [1973] who first suggested in fact that lightning-generated neutrons could explain anomalies in carbon dating and this interesting idea then prompted FPC to perform neutron-monitoring experiments in association with laboratory discharges that simulated the plasma conditions thought to exist in the lightning channel. FPC found no evidence for neutron production and, on the basis of this finding, set upper limits

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on the number of neutrons generated by lightning to 4 × 10^8 thermal neutrons and/or 7 × 10^{10}, 2.45 MeV neutrons per flash, in stark contrast to the value of 10^{15} originally estimated by Libby and Lukens.

[5] The first direct measurements of the neutron flux in the thunderstorm environment [*Fleischer*, 1975] yielded null results. Positive results were not obtained until ten years later when *Shah et al.* [1985] reported observing statistically significant enhancements in the neutron flux in correlation with thunderstorm EMP. These impressive experiments were conducted in the high mountainous (Himalayas, 2,743 m) region of Gulmarg, India, using an ingenious experimental configuration. A total of 11,200 EMP events were registered over a period of three years. Of those, 124 were associated with neutron measurements that yielded more than three neutrons (and up to 60) in 320 μs. On the basis of results obtained from random manual triggers in the absence of lightning, the latter count rate was considered to be a significant enhancement over the background. *Shah et al.* [1985] (hereinafter referred to as SRBA) estimated the average neutron yield to range from 10^7–10^{10} neutrons per lightning discharge assuming reaction ^{2}H(^{2}H, n)^{3}He with neutron energy ε_n = 2.45 MeV. From the measured delay times relative to EMP they deduced plausible yields extending to 2 × 10^{12} assuming ε_n as low as 0.023 eV. *Shyam and Kaushik* [1999] and *Kuzhewskij* [2004] have also communicated statistically significant single events, in which neutron bursts associated with atmospheric lightning discharges were detected near sea level in India and Moscow. Results of these successful experiments were interpreted as stemming from the nuclear fusion reaction ^{2}H(^{2}H, n)^{3}He within the lightning channel.

[6] The mechanisms by which neutrons could be generated by the lightning plasma are not well understood or even formulated. The nuclear fusion reaction ^{2}H(^{2}H, n)^{3}He has been mentioned often in connection with the hot lightning channel and the presence of water vapor. However, as noted for example in FPC, the maximum bulk plasma temperatures attained in lightning discharges (of order 3 eV) are far too low to initiate such reactions. An alternative mechanism rests in the speculations of CTR Wilson who advanced the idea that the acceleration of charged particles to very high energies by thundercloud electric fields could also lead to a decay or synthesis of atomic nuclei. In this paper we demonstrate, however, that the acceleration of deuterium ions to the threshold energies needed for fusion is impossible.

[7] In summary, this paper reexamines the problem of neutron production by thunderstorm discharges. It is shown that nuclear fusion cannot occur to any relevant or measurable degree under the electrical conditions prevalent in thunderstorms and that neutrons can instead be generated by photonuclear reactions associated with an electrical breakdown driven by relativistic runaway electrons as discussed by *Gurevich et al.* [1992] and developed further in a number of subsequent works [*Babich et al.*, 2004a, 2004b; *Gurevich and Zybin*, 2001; *Roussel-Dupré and Gurevich*, 1996]. The relativistic runaway breakdown mechanism is believed to occur in lightning discharges, including the gigantic upward atmospheric discharges (UAD) that develop above thunderclouds in volumes up to 1000 km^3 [*Babich et al.*, 2004a; *Gurevich and Zybin*, 2001; *Sentman and Wescott*, 1995].

[8] Neutron production by photonuclear reactions in air requires photon energies exceeding 10 MeV. In cases where neutron enhancements are measured this threshold requirement lends stronger support to the occurrence of relativistic runaway breakdown than to that of cold runaway [*Babich*, 2003] as discussed by *Dwyer and Smith* [2005].

2. Neutron Yield From Fusion Reactions

[9] The neutron yield expected in a lightning channel from the fusion reaction ^{2}H(^{2}H, n)^{3}He can be estimated as follows,

$$N_n \approx N_L P \cdot [\mathrm{H_2O}] \cdot 2[\%] \cdot S_{ch} l_{ch} n_{ion} \cdot \Delta t \cdot \int_{\varepsilon_{fus}}^{\infty} \mathrm{v}_{ion} f(\varepsilon_{ion}, T) \sigma_{fus}(\varepsilon_{ion}) d\varepsilon_{ion}, \quad (1)$$

where N_L is the number density of air molecules at standard temperature and pressure conditions (Loshmidt's number); P (in atm.) is the pressure at the altitude of interest; [H$_2$O] and [%] are respectively the relative concentrations of water vapor in a thunderstorm and deuterium molecules in natural water; ε_{ion}, v_{ion}, and n_{ion} are the kinetic energy, velocity, and number density of the deuterium ions; S_{ch} and l_{ch} are the cross-sectional area and length of the lightning channel; Δt is the life time of the strong electric field within the lightning channel ($\mathrm{v}_{ion} \cdot \Delta t \ll l_{ch}$); $\sigma_{fus}(\varepsilon_{ion})$ is the cross section for the nuclear fusion reaction; ε_{fus} is the minimum energy of deuterons, below which nuclear synthesis is inefficient within the framework of the considered problem. Note that equation (1) contains both the density of deuterium (= $N_L P \cdot [\mathrm{H_2O}] \cdot 2[\%]$) and the density of deuterium ions (n_{ion}) as required for the ^{2}H(^{2}H, n)^{3}He fusion reaction.

[10] *Kuzhewskij* [2004] justifies an efficient occurrence of the nuclear fusion reaction ^{2}H(^{2}H, n)^{3}He in the Earth's atmosphere by invoking the extremely large voltages associated with thunderstorms and the large currents in the lightning channel. The acceleration of charged particles, however, is controlled not by the total voltage drop, but by the strength of the electric field E, which in a thunderstorm is clearly insufficient for acceleration of deuterium ions to the energies required for fusion. The deuterium ion kinetics in air with an external electric field is captured in the elementary kinetic equation $eE \cdot \partial f/\partial\varepsilon_{ion} = -N_L P < \sigma_t > f$, where charge transfer is assumed to be the dominant process for deuterium ion interactions with air molecules. The solution of this equation gives the ion energy distribution function $f(\varepsilon_{ion})$ normalized to unity,

$$f(\varepsilon_{ion}, T) = T^{-1} \cdot \exp(-\varepsilon_{ion}/T). \quad (2)$$

The distribution is nearly Maxwellian with a temperature $T = eE/N_L P\langle\sigma_t\rangle$, where $\langle\sigma_t\rangle$ is the averaged charge transfer cross section. As according to Gamov's formula for σ_{fus} the rate of the reaction ^{2}H(^{2}H, n)^{3}He, $\sigma_{fus}(\varepsilon_{ion}) \cdot \mathrm{v}_{ion} \sim (\varepsilon_{ion})^{-0.5} \cdot \exp(-\mathrm{const}/\sqrt{\varepsilon_{ion}})$ is a weaker function of ε_{ion} than (2), the neutron yield can be estimated as follows

$$N_n \approx N_L P \cdot [\mathrm{H_2O}] \cdot 2[\%] \cdot S_{ch} l_{ch} n_{ion} \cdot \Delta t \cdot \langle \mathrm{v}_{ion} \sigma_{fus}(\varepsilon_{fus}) \rangle \cdot \exp(-\varepsilon_{fus}/T), \quad (3)$$

where $T \approx 1.7$ eV for the maximum macroscopic field strength observed in a thunderstorm $E \approx 1$ MV m^{-1} [*Bazelyan and Raizer*, 2001], $N_L \cdot P \approx 10^{25}$ m^{-3} (corresponds to an altitude of 7 km) and $\langle\sigma_t\rangle = 6 \times 10^{-20}$ m^2 (set to be equal to σ_t at the energy $\varepsilon_{ion} = 50$ eV [*Smith and Kevan*, 1971]). This result is comparable to the actual temperature $T \approx 3$ eV measured in the return stroke [*Bazelyan and Raizer*, 2001; *Orville*, 1968; *Rakov and Uman*, 2003]. At $T \approx 3$ eV and with $\varepsilon_{fus} = 1.7 - 6.6$ keV [*Bystritsky et al.*, 2003] where the cross section for the reaction ^{2}H(^{2}H, n)^{3}He has the extremely small value $\sigma_{fus} = 10^{-36}–10^{-32}$ m^2 [*Bystritsky et al.*, 2003], the absolute value of the index of the exponent in (3) is equal to 1000–6600. This value is so large that $N_n \ll 1$ for all reasonable values of geophysical quantities. Thus, for $l_{ch} = 1 - 10$ km, $S_{ch} \approx 1 - 10$ cm^2 [*Bazelyan and Raizer*, 2001], [H$_2$O] $\sim 1.65\%$ (according to a thickness of the besieged water layer [*Prokhorov*, 1988]), [%] = 0.015% [*Prokhorov*, 1988], $\Delta t \sim 50$ μs (typical duration of the return stroke [*Bazelyan and Raizer*, 2001; *Shah et al.*, 1985], σ_{fus}(6.6 keV) = 10^{-32} m^2 and $v_{ion} \sim 10^6$ m s^{-1} (corresponds to $\varepsilon_{ion} \approx 6.6$ keV) the factor before the exponent is less than 10^{10} even under the absolutely unrealistic condition of all deuterium atoms in the channel being ionized, so that $n_{ion} = N_L P \cdot [H_2O] \cdot 2[\%]$. Hence $N_n \ll 10^{-424}$ and the neutron yield resulting from nuclear fusion of deuterium atoms in the thermal environment and electrical fields associated with lightning can be considered negligible. The basic character of this result does not change over a wide range of potential values for the quantities included in formula (3) nor does it change when allowance is made for the contribution to the synthesis of fast deuterium atoms produced by charge transfer and subjected to strong drag in the dense atmosphere.

[11] Finally, to demonstrate that direct ion acceleration by the external field does little to enhance the reactions ^{2}H(^{2}H, n)^{3}He, it is sufficient to point out that for the breakdown strength of the macroscopic field E = 3 MV m^{-1} at $N = N_L$ the absolute value of the exponent in (3), for the values of ε_{fus} noted above, is in the range of 333–2200. Thus ion acceleration in the maximum electric fields that are likely to prevail in the hypothetical double layers of a channel of the return stroke as mentioned by *Shyam and Kaushik* [1999] is unlikely to produce any measurable neutron yield from nuclear fusion of deuterium. Even for fields that are 20–30 times the threshold for conventional breakdown (as required, for example, for the cold runaway process) the neutron yield remains extremely small compared to the projections of FPC and *Libby and Lukens* [1973].

[12] A collective acceleration of some number of deuterium ions captured by an accelerated electron beam, for instance ahead of the stepped leader or return stroke fronts, is a conceivable mechanism that could generate significant nuclear fusion in the lightning channel. The energy of ions moving with a velocity equal to that of electrons exceeds the electron energy by factor of $\sim m_p/m_e$. Even with a rather moderate velocity of joint motion of 6×10^8 cm s^{-1} (electron energy of 100 eV) the ion energy of 183 keV is more than sufficient for nuclear fusion. This kind of ion acceleration has been observed in laboratory experiments with evacuated acceleration tubes [*Graybill and Uglum*, 1970; *Plutto*, 1960; *Plutto and Kapin*, 1975; *Rander*, 1970; *Rander et al.*, 1970; *Vallis et al.*, 1981]. However, in the dense atmosphere charge transfer severely limits ion acceleration as in the case of the direct ion energization by the external field considered above.

3. Neutron Generation by Photonuclear Reactions

[13] X-rays and γ-rays have been measured in association with many forms of thunderstorm electrical discharges including the stepped leader [*Dwyer et al.*, 2005; *Moore et al.*, 2001], intracloud processes [*Eack et al.*, 1996; *McCarthy and Parks*, 1985], triggered lightning [*Dwyer et al.*, 2003], and high-altitude discharges [*Fishman et al.*, 1994; *Smith et al.*, 2005]. The spectral measurements for each of these categories have varied in available bandwidth but the authors have generally reported observing saturation in their detectors and concluded that the source must produce photon energies that extend beyond hundreds of keV to greater than 1–10 MeV [*Dwyer et al.*, 2004; *Fishman et al.*, 1994; *Moore et al.*, 2001; *Smith et al.*, 2005]. The largest spectral band was spanned by the measurements of *Smith et al.* [2005], who reported observing terrestrial γ-ray flashes (TGF) over an energy range from 20 keV to 20 MeV with a resolution of a few keV. TGFs are believed to originate from discharges that develop above a thunderstorm at altitudes exceeding ~15 km [*Dwyer and Smith*, 2005]. One form of UAD that could be responsible for TGFs is based on a quasi-electrostatic process as described by *Roussel-Dupré and Gurevich* [1996] and developed further by *Babich et al.* [2004b] and *Lehtinen et al.* [1999]. We will focus our initial discussion in this paper on the theoretical analysis of UADs presented by these authors (though we expect the conclusions to apply to all high-altitude discharges) and demonstrate that these processes fall short of reproducing the measurements of SRBA. The large distance in this case between the detector and the source translates into substantial attenuation of the neutron flux as a result of elastic scattering, capture, and r^{-2} spreading. The greater proximity of intracloud and leader discharges to the ground on the other hand has potential to yield greater neutron fluxes at the detector. However, in the absence of a complete theoretical treatment of the source and of extensive amplitude and spectral measurements of discharges at lower altitudes, it is difficult to make a definitive comparison with measurement.

3.1. UAD Mechanism

[14] UADs develop in part because of a generation of relativistic runaway electron avalanches (RREA) initiated by cosmic rays and are accompanied by pulses of rather hard γ-rays. The bremsstrahlung spectrum associated with this mechanism extends beyond 20 MeV and is consistent with the measurements of *Smith et al.* [2005] and with neutron generation by (γ, n) reactions. In the UAD model relativistic electrons are directed upward by the thunderstorm electric field until they become magnetized at an altitude *H*. At this point they begin to *E*x*B* drift horizontally with a magnitude defined by the horizontal component of the geomagnetic field and the vertical thunderstorm electric field [*Babich et al.*, 2004b]. Under the approximation of an isotropic point source of bremsstrahlung photons the num-

ber of photoneutrons generated per discharge can be estimated as follows:

$$
\begin{aligned}
N_{\mathrm{n}} = 2N_{\mathrm{L}}P(H) \cdot & \int_{H-h_{\mathrm{char}}}^{H+h_{\mathrm{char}}} e^{-x/h_{\mathrm{char}}}dx \int_{0}^{\Delta t_{\gamma}} \frac{dN_{\gamma}(\delta)}{dt} \\
& \cdot N_{\mathrm{e}}(\delta, t)dt \int_{\varepsilon_{\mathrm{th}}(\gamma,\mathrm{n})}^{\infty} f_{\mathrm{e}}\left(\delta, \varepsilon_{\gamma}\right)\sigma(\gamma, Sn)d\varepsilon_{\gamma} \\
& \approx 2N_{\mathrm{L}} \cdot \exp\left(-\frac{2H}{h_{\mathrm{char}}}\right) \cdot h_{\mathrm{char}}\left(e - \frac{1}{e}\right) \cdot N_{\mathrm{e}}(\delta) \cdot \frac{dN_{\gamma}}{dt}\Delta t_{\gamma} \\
& \cdot \sigma_{\mathrm{yield}}\left(\varepsilon_{\gamma,\max}\right) \cdot \langle f_{\gamma}(\delta, \varepsilon_{\mathrm{th}})\rangle, \qquad (4)
\end{aligned}
$$

where an exponential altitude variation for the air density with a characteristic scale $h_{\mathrm{char}} \approx 7.1$ km is assumed, $dN_{\gamma}(\delta)/dt$ is the rate of photon emission, Δt_{γ} is the duration of the pulse of atmospheric γ radiation detected from on board the orbital observatory [*Fishman et al.*, 1994; *Smith et al.*, 2005], $N_{\mathrm{e}}(\delta)$ is the number of relativistic runaway electrons in the air at the overvoltage $\delta = eE/F_{\min}$ defined relative to the minimum of the electron drag force $F_{\min} = 218$ keV $(\mathrm{m} \cdot \mathrm{atm.})^{-1}$, $f_{\gamma}(\delta, \varepsilon_{\gamma})$ is the photon distribution function normalized to unity, $\sigma(\gamma, Sn) = \sum i \cdot \sigma(\gamma, i \cdot n) + \nu\sigma(\gamma, f)$, $\sigma(\gamma, i \cdot n)$ is the cross section of the reaction $(\gamma, i\mathrm{n})$ with the yield of i neutrons, $\sigma(\gamma, f)$ is the photonuclear fission cross section with a yield of ν neutrons, $\sigma_{\mathrm{yield}}(\varepsilon_{\gamma,\max}) = \int_{\varepsilon_{\mathrm{th}}(\gamma,1\mathrm{n})}^{\varepsilon_{\gamma,\max}} \sigma(\gamma, Sn)\, d\varepsilon$ is the total photoneutron yield cross section, $\varepsilon_{\mathrm{th}}(\gamma, 1n)$ is the $(\gamma, 1\mathrm{n})$ reaction threshold, $\varepsilon_{\gamma,\max}$ is the maximum energy up to which photonuclear cross-section data are available. As a first approximation it is sufficient to focus our attention on the atmospheric ^{14}N nuclei, for which $\varepsilon_{\mathrm{th}}(\gamma, 1\mathrm{n}) = 10.55$ MeV, $\varepsilon_{\gamma,\max} = 29.5$ MeV, $\sigma_{\mathrm{yield}} = 98.8 \times 10^{-31}$ MeV $\cdot$ m^2 [*Dietrich and Berman*, 1988]. Letting $\delta = 4$ ($H = 30$ km) [*Babich et al.*, 2004b], $\Delta t_{\gamma} \approx 1$ ms [*Fishman et al.*, 1994; *Smith et al.*, 2005] (this time includes a series of RREA generations [*Babich et al.*, 2004b]), $\langle f_{\gamma}(\delta, \varepsilon_{\gamma})\rangle > \frac{1}{\varepsilon_{\gamma,\max} - \varepsilon_{\mathrm{th}}(\gamma, n)} \int_{\varepsilon_{\mathrm{th}}(\gamma,\mathrm{n})}^{\varepsilon_{\gamma,\max}} f_{\gamma}(\delta, \varepsilon_{\gamma})d\varepsilon_{\gamma} \approx 5 \times 10^{-4}$ MeV^{-1}, $dN_{\gamma}(\delta)/dt \approx 10^{7}$ (s·atm.·electron)$^{-1}$ [*Babich et al.*, 2004a] and $N_{\mathrm{e}}(\delta) = 10^{17}$, i.e., equal to the number of electrons sufficient to generate at the altitude $H \approx 30$ km the number of hard photons detected by *Fishman et al.* [1994], we obtain the very large value $N_{\mathrm{n}} \approx 10^{15}$. This evaluation is rather conservative. It does not vary essentially, assuming the relativistic electron number to be constant, within reasonable limits of the other values included in formula (4). In particular changing the generation volume defined by the length $2h_{\mathrm{char}}$ in the first integral of equation (4) by the mean free path of photons with energies in the range $[\varepsilon_{\mathrm{th}}(\gamma, 1\mathrm{n}), \varepsilon_{\gamma,\max}]$ at the altitude H does not crucially affect the result for N_{n}.

3.2. Intracloud Mechanism

[15] A rough estimate of the number of neutrons generated by an intracloud discharge can be obtained from equation (4) and the γ-ray measurements of *Dwyer et al.* [2004]. The latter paper describes a triggered lightning experiment that initiated a discharge in an overlying thunderstorm at 6–8 km from three NaI crystals fielded on the ground for the purposes of detecting γ-ray bursts. A 300 μs burst characterized by a spectrum extending from 1 to 10 MeV was measured in this experiment some 20 ms following the vaporization of the copper wire used in the lightning triggering process. The total number of photons in the burst summed to 227. Assuming a nominal distance to the discharge of 7 km and an atmospheric attenuation factor of 3×10^{6} (or several million as noted by the authors), one finds a total of $\sim 3 \times 10^{19}$ photons at the source. Substituting this value for $\frac{N_{\gamma}(\delta)}{dt} \cdot \Delta t_{\gamma} \cdot \mathrm{N_e}(\delta, t)$, assuming a source length equal to ~ 50 m (nominal leader dimension), and taking $H = 5.7$ km (i.e., 3 km from the neutron detector) yields $N_{\mathrm{n}} = 4 \times 10^{13}$, a factor of 25 smaller than the UAD value.

4. Photoneutron Number at the Detector

4.1. UAD Mechanism

[16] In view of the fact that the neutron detector in the work of *Shah et al.* [1985] was located at an altitude above sea level, $h_{\mathrm{det}} \approx 2.7$ km, that is much less than H, the neutron flux produced by a UAD will suffer considerable attenuation before reaching the detector. The number of neutrons at the detector can be estimated by the formula for a point neutron source:

$$
N_{\mathrm{n}}(\mathrm{det}) \approx \frac{\eta S_{\mathrm{det}} N_{\mathrm{n}}}{4\pi(H - h_{\mathrm{det}})^{2}} \cdot F(\Sigma_{\mathrm{n}} h_{\mathrm{char}},\ h_{\mathrm{det}}/h_{\mathrm{char}}), \qquad (5)
$$

where $F = \Sigma_{\mathrm{n}} h_{\mathrm{char}} \cdot \exp(-h_{\mathrm{det}}/h_{\mathrm{char}}) \cdot \exp\{-\Sigma_{\mathrm{n}} h_{\mathrm{char}} \cdot \exp(-h_{\mathrm{det}}/h_{\mathrm{char}})\}$ accounts for the exponential attenuation of the neutron flux in the atmosphere with accommodation for an accumulation factor. Here $\eta = 0.03$ is the detection efficiency, $S_{\mathrm{det}} = 3$ m^2 is the effective area of the detector [*Shah et al.*, 1985], $\Sigma_{\mathrm{n}} = 2N_{\mathrm{L}} \cdot (\sigma_{\mathrm{c}}(\langle\varepsilon_{\mathrm{n}}\rangle) + \sigma_{\mathrm{s}}(\langle\varepsilon_{\mathrm{n}}\rangle))$ is the total macroscopic cross section for capture (c) and elastic scattering (s) of neutrons with a mean energy $\langle\varepsilon_{\mathrm{n}}\rangle$ by air nuclei at sea level. According to the data obtained by *Abagyan et al.* [1981] on elementary cross sections $\Sigma_{\mathrm{n}} \cdot h_{\mathrm{char}} \approx 44.2$ for $\langle\varepsilon_{\mathrm{n}}\rangle \approx 0.5 \cdot (\varepsilon_{\gamma,\max} - \varepsilon_{\mathrm{th}}(\gamma, 1\mathrm{n})) \approx 9.5$ MeV. As a result (5) gives a value $N_{\mathrm{n}}(\mathrm{det}) \approx 3 \times 10^{-8}$ meaning that neutrons from the point source located in stratosphere do not penetrate through to the detector altitude. A direct simulation of the neutron transport by the Monte-Carlo technique yields $F \approx 6 \times 10^{-12}$, to which corresponds $N_{\mathrm{n}}(\mathrm{det}) \approx 5 \times 10^{-8}$ neutrons with a mean energy close to 1 MeV.

[17] In air even at $N = N_{\mathrm{L}}$ the mean free path λ_{γ} of photons with energies 10–50 MeV is in the range 450–570 m [*Grechukhin*, 1998]. Thus a number of photons with energies $\varepsilon > \varepsilon_{\mathrm{th}}(\gamma, 1\mathrm{n})$ produced at the UAD altitudes could reach the surface layers of the atmosphere. It is necessary then in calculating $N_{\mathrm{n}}(\mathrm{det})$ to allow for a cascade process where downward spreading photons generate neutrons. In the framework of a mono-energetic gamma source and a one-dimensional approximation the absorption of photons is described by the equation

$$
\begin{cases}
-\dfrac{dN_{\gamma}(x)}{dx} = -\dfrac{1}{\lambda_{\gamma}} e^{-\frac{x}{h_{\mathrm{char}}}} N_{\gamma}(x), \\
N_{\gamma}(x = H) = N_{\gamma}(H),
\end{cases} \qquad (6)
$$

where the number of photons at the altitude H (source) is estimated as

$$N_\gamma(H, \varepsilon_\gamma) \approx N_e(\delta) \cdot \exp\left(-\frac{H}{h_{\rm char}}\right) \cdot \frac{dN_\gamma}{dt} \Delta t_\gamma \cdot f_\gamma(\delta, \varepsilon_\gamma) d\varepsilon_\gamma. \quad (7)$$

Solution of equation (6) yields the number of photons at the altitude $x \in [h_{\rm det}, H]$ to be:

$$N_\gamma(x, \varepsilon_\gamma) = \frac{N_\gamma(H, \varepsilon_\gamma)}{4\pi x^2} \cdot \exp\left[\frac{h_{\rm char}}{\lambda_\gamma(\varepsilon_\gamma)} \cdot \left(e^{-\frac{H}{h_{\rm char}}} - e^{-\frac{x}{h_{\rm char}}}\right)\right]. \quad (8)$$

The coordinate x is directed upward against the photon flux.

[18] The photons generate $dN_{\rm n}(x)$ neutrons in a layer dx (elementary neutron source):

$$dN_{\rm n}(x) \approx 2N_L \exp\left(-\frac{x}{h_{\rm char}}\right) \cdot 4\pi x^2 dx \int\limits_{\varepsilon_{\rm th}(\gamma, {\rm n})}^{\infty} N_\gamma(x, \varepsilon_\gamma) \sigma(\gamma, Sn) d\varepsilon_\gamma. \quad (9)$$

The attenuation of the neutron flux in the same approximation is described similarly:

$$\begin{cases} -\dfrac{dN_{\rm n}(\xi)}{dx} = -\Sigma_{\rm n} e^{-\frac{\xi}{h_{\rm char}}} N_{\rm n}(\xi), \\ N_{\rm n}(\xi = x) = dN_{\rm n}(x), \end{cases} \quad (10)$$

where $\xi \in [h_{\rm det}, x]$. Allowing for the accumulation factor $x\Sigma_{\rm n} \cdot e^{-\frac{x}{h_{\rm char}}}$, the number of neutrons that reach the detector, can be estimated as follows

$$dN_{\rm n}({\rm det}) \approx \frac{dN_{\rm n}(x)}{4\pi(x - h_{\rm det})^2} \cdot x\Sigma_{\rm n} e^{-\frac{x}{h_{\rm char}}} \cdot \exp\left\{\Sigma_{\rm n} h_{\rm char}\left(e^{-\frac{x}{h_{\rm char}}} - e^{-\frac{h_{\rm det}}{h_{\rm char}}}\right)\right\}. \quad (11)$$

The total number of neutrons recorded by the detector is estimated by the integral

$$N_{\rm n}({\rm det}) \approx 2N_L \exp\left(-\frac{H}{h_{\rm char}}\right) \cdot N_e(\delta) \cdot \frac{dN_\gamma}{dt} \Delta t_\gamma \cdot \sigma_{\rm yield}(\varepsilon_{\gamma,\max}) \cdot \langle f_\gamma(\delta, \varepsilon_{\rm th})\rangle \cdot \eta S_{\rm det} \cdot \int\limits_{h_{\rm char}+h_{\rm det}}^{H} \frac{\exp\left\{-\frac{2x}{h_{\rm char}} + \frac{h_{\rm char}}{\lambda_\gamma}\left(e^{-\frac{H}{h_{\rm char}}} - e^{-\frac{x}{h_{\rm char}}}\right) + \Sigma_{\rm n} h_{\rm char}\left(e^{-\frac{x}{h_{\rm char}}} - e^{-\frac{h_{\rm det}}{h_{\rm char}}}\right)\right\}}{4\pi(x - h_{\rm det})^2} \Sigma_{\rm n} x dx \quad (12)$$

with a lower limit selected so as to avoid the nonphysical divergence at $x = h_{\rm det}$. Thus $N_{\rm n}$(det) is somewhat underestimated. Letting λ_γ = 500 m (at $\varepsilon_\gamma \approx$ 20 MeV [*Grechukhin*, 1998]) we obtain $h_{\rm char}/\lambda_\gamma \approx 14.2$. As a result (12) gives $N_{\rm n}({\rm det}) \approx 10^{-4}$. The proximity of the evaluation $N_{\rm n}$(det) by the formula (5) and the results of Monte Carlo simulations justify the estimation (12).

4.2. Intracloud Mechanism

[19] For this case the source is assumed to be a distance d_{source} = 3 km from the detector and it is sufficient to use equation (5) to estimate the number of neutrons at the detector. With $\Sigma_{\rm n} \cdot h_{\rm char} = \Sigma_{\rm n} \cdot d_{source} \approx 18.7$ and $N_n = 4 \times 10^{13}$ we find $N_{\rm n}({\rm det}) \approx 1$. This result is in basic agreement with the lower numbers measured by *Shah et al.* [1985] and suggests that low-altitude discharges rather than UADs are the source of neutrons in this experiment.

[20] A detailed simulation of neutron production by the runaway process in the thunderstorm electrical environment is required to establish a direct link with the measurements. However, this feasibility analysis does suggest that neutrons can be produced in sufficient numbers by this mechanism.

5. Neutron Delay Times

[21] The measured delay times $t_{\rm del}$ for neutron arrival at the detector relative to that of lightning EMP range from 10 μs to 0.1 s, with the number of neutron events decreasing as $t_{\rm del}$ increases [*Shah et al.*, 1985]. Assuming line-of-sight motion of fusion neutrons with energies of $\varepsilon_{\rm n}$ = 1 – 10 MeV, these time delays point to neutron sources located at distances from hundreds of meters to thousands of kilometers from the detector. SRBA explained the large $t_{\rm del}$ as follows: (1) Reactions ^{12}N(^{2}H, n)^{13}C and ^{14}N(^{2}H, n)^{15}O are occurring in addition to ^{2}H(^{2}H, n)^{3}He, and these reactions generate neutrons with smaller energies. (2) The first stroke of any given flash only triggers the recording system, but the neutrons are [*Shah et al.*, 1985, p. 774] "...generated in a succeeding stroke belonging to the same or a different flash." (3) Neutrons diffuse in air before they hit the detector. Despite the large concentration of nitrogen nuclei, especially in trees, relative to deuterium, fusion reactions involving these species are as impossible in the lightning channel as are any other form of fusion. In addition, cross sections for the above reactions are much less than that of ^{2}H(^{2}H, n)^{3}He.

[22] In the framework of the photonuclear mechanism the wide range of $t_{\rm del}$ can be explained by the fact that neutrons are generated in a large volume along the path of the photons propagating downward from high altitudes, as in the case of UADs, and in the ground as well as the detector material. Also, unlike the nuclear fusion neutrons, the photoneutrons are distributed over a wide range of energies $\varepsilon_{\rm n} = \varepsilon_\gamma - \varepsilon_{\rm th}$ (γ, 1n).

[23] For UADs, large initial time delays in neutron arrival are observed provided the source of the first (line-of-sight) neutron with large energy is at a great distance from the detector, as is assumed in (5). Small delays are a consequence of neutron generation by the photons reaching the surface layers of the troposphere as is included in (12). The UAD neutron source however has trouble accounting for values of $t_{\rm del} \leq 100$ μs, as the time required for photons to propagate from UAD altitudes to the detector is itself close to 100 μs.

[24] The low-altitude sources can account for large initial time delays by assuming production of low-energy neu-

trons, an increased path resulting from scattering, or multiple sources as invoked by SRBA. SRBA mentioned an event in which 33 neutrons generated by lightning that struck a tree located at 400 m from the detector were registered. The delay time $t_{\mathrm{del}} \approx 72$ ms corresponding to this event is not consistent with nuclear synthesis in the lightning channel, but is very consistent with the photonuclear mechanism of neutron generation by either UAD γ bursts or leader discharges.

6. Conclusion

[25] The neutron yield of photonuclear reactions that accompany atmospheric γ-ray bursts associated with lightning discharges of various forms is estimated to lie between $\sim 10^{13}$–10^{15} per discharge, whereas nuclear fusion is impossible under the physical conditions presently believed and measured to exist in the lightning channel. In the case of UADs the minimum number of REs, namely 10^{17}, estimated on the basis of the mechanism proposed by *Gurevich et al.* [1992] and sufficient to match the terrestrial γ-ray pulses [*Fishman et al.*, 1994; *Smith et al.*, 2005], is not sufficient to explain, in the framework of a simple model, the neutron flux enhancement observed in the atmosphere in correlation with thunderstorm activity [*Shah et al.*, 1985]. A detailed numerical simulation of a UAD with a self-consistent account of the γ-ray and neutron generation and transport at large distances along with a proper modeling of the conditions of the observations is required before a definitive conclusion can be reached.

[26] A rough estimate of the neutron yield from leader processes, on the other hand, is in better agreement with the data provided the source is assumed to produce energetic photons (>10 MeV) in sufficient quantity and to approach within a few kilometers of the detector. The γ-ray spectrum associated with leader activity is not, however, well characterized. *Moore et al.* [2001] identified the presence of photons with energy > 1 MeV in their measurements while *Dwyer et al.* [2005] observed a spectrum with energies <1 MeV. The analysis presented in 3B and 4B above was an extrapolation of the photon flux, measured by *Dwyer et al.* [2004] and believed to have originated from a discharge in the thunderstorm 6–8 km from the gamma detectors, to the case of a leader that was assumed to approach within 3 km of a hypothetical neutron detector. The gamma spectrum measured in that case extended out to 10 MeV. The feasibility of this mechanism as a neutron generator needs to be tested, as in the case of UADs, by means of detailed simulations that include runaway breakdown and reproduce leader discharges.

[27] A simultaneous measurement (within the limits of neutron time delays) of γ-rays, neutrons, and EMP would provide unambiguous confirmation of the photonuclear mechanism for neutron production posited in this article. Proving the connection between atmospheric neutron flux enhancements and lightning discharges would be a strong argument in favor of the occurrence/importance of relativistic runaway breakdown and the production of energetic (>10 MeV) photons in these discharges. The lack of such a link would mean that the correlation of the multineutron events with thunderstorm EMPs discovered by SRBA is only occasional, that is doubtful in view of careful selection of these events, or would signal the occurrence, in the lightning channel, of some kind of local processes with characteristic times much less than a microsecond.

[28] Given that neutrons generated by atmospheric discharges have been detected, it is interesting, following *Libby and Lukens* [1973], to analyze the effect of radiocarbon ^{14}C production by thunderstorms on the basis of our estimate of neutron numbers from atmospheric discharges. For the ^{14}C production in the atmosphere the reactions n(^{13}C, γ)^{14}C and n(^{14}N, ^{14}C)^{1}H are responsible [*Kikoin*, 1976]. The rate of radiative capture n(^{13}C, γ)^{14}C is $R_{\mathrm{n}\gamma} = \sigma_{\mathrm{n}\gamma} \times \mathrm{v_n} \approx 10^{-28}$ m^3 s^{-1} almost independently of the neutron energy because the cross section $\sigma_{\mathrm{n}\gamma}$ is inversely proportional to $\mathrm{v_n}$. For example, for thermalized neutrons $\sigma_{\mathrm{n}\gamma} \approx 0.5 \times 10^{-31}$ m^2 and $\mathrm{v_n} \approx 2.2 \times 10^3$ m s^{-1} [*Kikoin*, 1976]. The rate of n(^{14}N, ^{14}C)^{1}H is $R_{\mathrm{np}} = \sigma_{\mathrm{np}} \times \mathrm{v_n} \approx 4 \times 10^{-25}$ m^3 s^{-1} also almost independently of the neutron energy. For thermalized neutrons $\sigma_{\mathrm{np}} \approx 1.75 \times 10^{-28}$ m^2 [*Kikoin*, 1976]. Hence n(^{14}N, ^{14}C)^{1}H dominates over n(^{13}C, γ)^{14}C, especially in view of the very low CO_2 concentration in the atmosphere and the relative volumetric concentration of the isotope ^{13}C: correspondingly 3.5×10^{-2}% and 1.1% [*Prokhorov*, 1988]. As follows from cross sections $\sigma_{\mathrm{np}} \approx 1.75 \times 10^{-28}$ m^2 and $\sigma_{\mathrm{n}\gamma} \approx 0.08 \times 10^{-28}$ m^2 [*Kikoin*, 1976] the reaction n(^{14}N, ^{14}C)^{1}H dominates over the radiative capture n(^{14}N, γ)^{15}N. At sea level the frequency of n(^{14}N, ^{14}C)^{1}H is $N(^{14}\mathrm{N}) \times R_{\mathrm{np}} \approx 0.8 \times 5.4 \times 10^{25}$ m^{-3} $\times$ 4×10^{-25} m^3 s^{-1} ≈ 17 s^{-1}. Consequently during times much less than the neutron life time $t_{\mathrm{n}} = 898$ s [*Prokhorov*, 1988] the neutron flux will be absorbed completely mainly because of n(^{14}N, ^{14}C)^{1}H. This is the case even at the altitude of the upper troposphere of $\sim$10 km. Hence a number of ^{14}C nuclei produced by $N_{\mathrm{n}} = 10^{15}$ neutrons (our maximal prediction) can be estimated as $N(^{14}\mathrm{C}) \approx N_{\mathrm{n}} \times R_{\mathrm{lightning}} \times \delta_{\mathrm{n\text{-}lightning}}/V_{\mathrm{trop}} \approx 2 \times 10^{-4}$ m^{-3} s^{-1}. Here $R_{\mathrm{lightning}} \approx 100$ s^{-1} is the lightning rate throughout the globe, $\delta_{\mathrm{n\text{-}lightning}} \approx 10^{-2}$ is the portion of neutron producing lightning strokes [*Shah et al.*, 1985], $V_{\mathrm{trop}} \approx 4\pi(R_{\mathrm{earth}})^2 \times l_{\mathrm{trop}}$ is the troposphere volume, $R_{\mathrm{earth}} \approx 6370$ km is the Earth's radius and $l_{\mathrm{trop}} \approx 10$ km is the troposphere height. This estimate assumes that nuclei ^{14}C generated by thunderstorms are transported by atmospheric flows throughout the Earth's surface. Naturally initially they are concentrated in the regions of severe thunderstorm activity in the tropical belt. The value $N(^{14}\mathrm{C}) \approx 2 \times 10^{-4}$ m^{-3} s^{-1} is much less than 1.85×10^{-2} m^{-3} s^{-1} [*Prokhorov*, 1988], produced at sea level because of the cosmic irradiation. Thus thunderstorm-produced neutrons nowadays deposit weakly into the radiocarbon concentration on average across the globe. However, if we assume that some sizable fraction of the ^{14}C is deposited locally (e.g., absorbed by the local biota) on a time short compared to the redistribution by circulation, and account for the fact that lightning is concentrated over land and that the lightning rate varies by orders of magnitude over various regions then it is possible for lightning-produced ^{14}C to compete with the cosmic irradiation in these regions as suggested by FPC.

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