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Nuclear reactions in the uppermost Earth atmosphere as a source of the magnetospheric positron radiation belt

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Abstract. A physical mechanism for the formation of a natural positron belt in the Earth's magnetosphere is considered. It is assumed that a natural source of energetic positrons as well as electrons can be created owing to the decay of charged pions $\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$, which have their origin in nuclear collisions between energetic trapped inner zone protons and heavier atoms (He and O) in the upper atmosphere of the Earth. Simulations of these processes demonstrate that there is a predominant production of positive pions over negative pions, and consequently the decays result in a substantial excess of positrons over electrons at energies greater than tens of MeV. This positron excess is found to be energy-dependent and to decrease with increasing incident proton energy; this excess is essentially absent at proton energies corresponding to cosmic ray primaries of ≥8 GeV. Our numerical computations for the resulting e^+/e^- fluxes provide ratio values of ~4 at multi-MeV energies and at $L = 1.2 \pm 0.1$. The simulation results presented herein are compared to the existing and recent experimental evidence.

1. Introduction

The likely existence of significant fluxes of geomagnetically trapped antiparticles in the innermost magnetosphere of the Earth has been demonstrated in recent papers [*Gusev et al.*, 1996; *Pugacheva et al.*, 1997]. These antiparticles (positrons and antiprotons) are not of primordial or direct extraterrestrial origin but are expected as the natural products of nuclear reactions of high-energy trapped protons (TPs) confined in the terrestrial radiation belt and primary cosmic rays (CRs) with the ambient neutral atoms of the terrestrial atmosphere residing at several hundred kilometers altitudes. The subsequent trapping and storage of these charged antiparticles within the magnetosphere result in the formation of radiation belts similar to those of protons, electrons, and anomalous CR nuclei. From the computations presented herein we expect the presence of trapped energetic multi-MeV positron fluxes in a narrow L shell range in the innermost magnetosphere, low enough for heavy neutrals to be abundant and high enough for radiation belt protons to have appreciable fluxes to induce the antiparticle generation effects.

Since the 1960s, attempts have been made to unambiguously detect the presence of positrons in the Earth's vicinity. In balloon experiments carrying instruments with magnets, *De Shong et al.* [1964] and *Hartman et al.* [1965] made the first attempts to observe interplanetary positrons in the energy range of 50 MeV to several GeV. Through the detection of 0.511-MeV annihilation quanta, *Cline and Hones* [1968] identified the presence of low-energy positrons (0–3 MeV) of interplanetary origin in experiments carried on the OGO 1 and III spacecraft. The SMM spacecraft observations of geomagnetically trapped multi-MeV positron fluxes in the 1980s [*Share et al.*, 1989; *Hones and Higbie*, 1989; *Rieger et al.*, 1989], however, are mostly to be viewed in the context of particle leakage from nuclear reactors orbiting on board the Russian Cosmos satellites.

Measurements of cosmic ray positrons with energies above 0.3 GeV, with a sophisticated experimental technique using standard and superconductive magnets, have been carried out over a number of years, and the details have been recently reported [i.e., *Boezio et al.*, 2000, and references therein]. The aim of these high-energy experiments is to detect primary CR positrons. However, until now, the observed positron CR flux attested to the origin being purely secondary in nature; that is, positrons are generated in nuclear reactions of primary cosmic rays with interstellar matter well beyond the Earth.

The hypothesis that a high-energy positron/electron radiation belt of nuclear origin could be locally generated in the Earth's uppermost atmosphere was first considered by *Basilova et al.* [1982]. Experiments on board the Russian Cosmos-1669 satellite and on the Mir space station provided measurements of fluxes of magnetospheric positrons and electrons with energies from 20 to 150 MeV. The results showed higher positron fluxes within the Brazilian Magnetic Anomaly (BMA) region compared to the fluxes outside of this region [*Voronov et al.*, 1987], and the results indicated an excess of electrons over positrons in the BMA region itself [*Galper et al.*, 1997].

More recently, the Alpha Magnetic Spectrometer (AMS) on

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board the space shuttle *Discovery* detected a surprisingly large four times excess of positrons over electrons at energies >150 MeV in the equatorial region of the inner magnetosphere at altitudes of around 400 km [*AMS collaboration*, 1999, 2000].

Freden and White [1960] have pointed out that the trapped high-energy protons could locally produce a variety of isotopes of the lighter elements, such as deuterium (D), tritium (T), and ^{3}He in nuclear interactions with heavy atoms of the residual atmosphere. Instrumentation on board the Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX) and CRRES satellites recently confirmed this expectation, reporting the presence of D and ^{3}He isotope radiation belts in the Earth's inner radiation zone [*Selesnick and Mewaldt*, 1996; *Chen et al.*, 1996]. In summary, these recent observations all support the hypothesis that the rarefied upper atmosphere at altitudes of 300–1000 km, with its height-dependent content of different thermal atomic neutral species, is the locus for the generation of noticeable fluxes of energetic secondary electrons, positrons, and various daughter-nuclei ionic species confined in the magnetosphere.

The same kind of nuclear interactions are naturally valid for the production of energetic antiparticles in the magnetospheres of the other magnetized planets in our solar system. It is reasonable to assume further that during magnetic disturbances, energetic particles as well as energetic antiparticles can also precipitate into the planetary atmospheres or escape into the surrounding interplanetary medium, resulting in relatively short timescale variations of positron and antiproton interplanetary fluxes. These effects might be small for the Earth's environment but could be especially pronounced for the Jovian and Saturnian magnetospheric environments.

In our modeling we consider the resulting values of the e^+/e^- flux ratio that is expected from the nuclear reaction source mechanism outlined above. This ratio is an important characteristic of the positron flux source function, and it could be used as an indicator in the analysis of experimental data concerning magnetospheric positrons.

2. Nuclear Reaction Source of Magnetospheric Positrons

The positrons and electrons considered here are not generated as direct products of inelastic nuclear reactions in the Earth's exosphere; this is in contrast to the direct generation of the D, T, and ^{3}He isotopes. Rather, they are predominantly formed in the decay of short-lived charged pions and kaons ($\pi^\pm \rightarrow \mu^\pm + \upsilon$; $\mu^\pm \rightarrow e^\pm + \upsilon + \tilde{\upsilon}$) that are generated in the nuclear collisions, and they are therefore intrinsic meson instability decay products. The minimum proton energy threshold for π-meson production is $\approx$290 MeV.

Because of the short lifetimes of pions ($\tau_\pi = 2.8 \times 10^{-8}$ s) and muons ($\tau_\mu = 2.2 \times 10^{-6}$ s), the resulting positrons and electrons are effectively produced in the same region where the parent pions and muons are born. Pions and muons of 1 GeV travel distances of 56 and 6.2 km, respectively, before decaying. Thus the electrons and positrons produced by this nuclear mechanism will be essentially confined to the same L shells as those of their parent TPs.

In the chain of unstable particle decays, the mean fractions of energy carried away by a muon in the $\pi^\pm \rightarrow \mu^\pm + \upsilon$ decay is $q_\mu = 0.8$, and that carried away by an electron in the $\mu^\pm \rightarrow e^\pm + \upsilon + \tilde{\upsilon}$ decay is $q_e = 0.33$. The production spectrum of electrons, $P_{e^\pm}(E_e)$ (i.e., the number of particles generated by a unit incident proton flux in 1 g cm^{-2}), is related to that of the pion spectrum $P_{\pi^\pm}(E_\pi)$ as $P_{e^\pm}(E_e) = P_{\pi^\pm}(E_e/q_\mu q_e)/q_\mu q_e$. This means that the ratio of e^+/e^- in the production spectra at energy E_e is the same as the ratio in the production spectra of the parent pions at the corresponding pion energy $E_\pi = E_e/q_\mu q_e$. The differential electron flux, $F_e(E_e)$, of energy E_e at the point of observation is determined by the particle conservation law: $F_e(E_e) = P_e(>E_e)/(dE/dx)$, where $P_e(>E_e)$ is the integral electron production spectrum.

Accordingly, the ratio of the resulting differential fluxes of e^+ and e^- is equal to the ratio of the integral production spectra of positrons to electrons at the same energy, and it is also equal to the ratio of the integral production spectra of the pions with energies corresponding to $1/q_e q_\mu$ times the positron/electron energy:

$$F_{e^+}(E_e)/F_{e^-}(E_e) = P_{e^+}(>E_e)/P_{e^-}(>E_e)$$
$$= P_{\pi^+}(>E_e/q_\mu q_e)/P_{\pi^-}(>E_e/q_\mu q_e).$$

This relation permits us to substitute the rather complicated modeling of the absolute fluxes of positrons and electrons by the much simpler computation of the pion production spectra for the various incident proton energies.

Qualitatively, the excess of positrons over electrons is a natural consequence of the $A(p, \pi)$ nuclear reactions, in which $D + \pi^+$, $p + \pi^+$, and $p + n + \pi^+$ products predominate near the proton reaction threshold energy [*Machner and Hidenbauer*, 1999] (here A is a target atomic number). The trapped component has comparatively greater fluxes of protons at an energy close to the reaction threshold than do CR protons to provide a substantial positron excess.

To estimate $F_{e^+}(E_e)/F_{e^-}(E_e)$ flux ratios in the region of $L = 1.2 \pm 0.1$, where intense TP fluxes are present, we have computed the production spectra of pions produced by protons with TP energies 300 MeV to 2 GeV and by the CR protons (>8 GeV). In the equatorial region at $L = 1.2$ the TP fluxes are predominantly located in a narrow pitch angle range of 90 ± 10°. Thus, in this modeling we took into consideration only the pions born with velocity vectors parallel to those of the parent protons, because only they produce positrons and electrons that can be trapped.

The others, generated with angles beyond this range, after decay, produce quasi-trapped particle fluxes with about the same e^+/e^- flux ratio. Most pions are born in the narrow angle range of about ±30° to the velocity vector of a parent proton, and because of that, they do not significantly contribute to albedo fluxes. As thermal He is an essential constituent of the Earth's upper atmosphere at altitudes of ~800 km (the minimum altitude of the $L = 1.2$ geomagnetic field lines at the geomagnetic equator), the modeling utilized the He(p, π) reactions. Besides, the charged pion production has a weak dependence on the target atomic number A. To obtain the pion production output we used a well-tested version of the Monte Carlo computer code SHIELD for the intranuclear cascade simulations [*Dementyev and Sobolevsky*, 1999].

In Figure 1 the results of our Monte Carlo simulations of the He(p, π) pion production are presented. The ratio of the integral production spectra of π^+ and π^- mesons at energies of ~100 MeV, produced by the protons in the energy range 0.3–2.0 GeV, lies between 2 and 5 and increases with pion energy. This positron excess is a direct consequence of the charge conservation law, which tends to favor positive pion production when only a few pions are born. In contrast, the

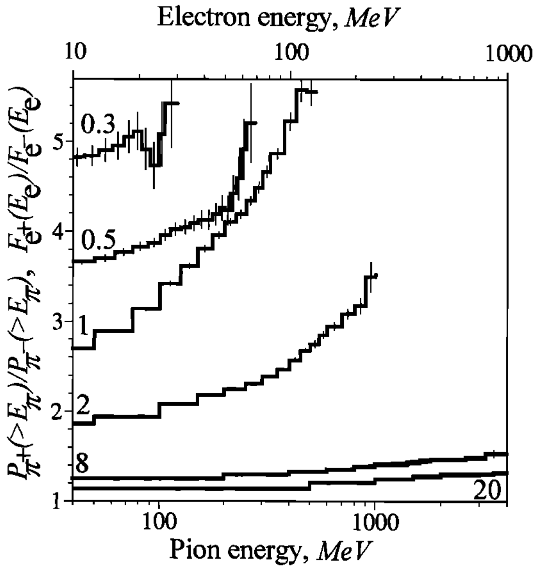

Figure 1. The results of Monte Carlo simulations of the dependence of the ratio of the integral production spectra of pions $P_{\pi^+}(>E_\pi)/P_{\pi^-}(>E_\pi)$ on pion energy E_π and of the differential flux ratio of positrons to electrons, $F_{e^+}(E_e)/F_{e^-}(E_e)$, on electron energy E_e produced by protons with different energies. The error bars show the statistical errors of the simulation. The numbers near the curves mark the parent proton energy in GeV.

protons of CR energies (>8 GeV) produce a greater number of pions, and the π^+/π^- ratio at these energies is almost equal to unity. Thus collision-induced nuclear reactions of the trapped protons of 0.3–2 GeV substantially favor the production of positrons over electrons in the energy range of ~20 MeV to several hundreds of MeV.

The estimates of the e^+/e^- flux ratio, obtained in these nuclear reactions, with both the energetic TP spectrum from AP-8 model [*Vette*, 1991] and the CR spectrum in the equatorial region, are presented in Figure 2. In the $L = 1.2 \pm 0.1$ region in the energy range of $E_e = 40$–1500 MeV the TP source produces more positrons than electrons by a factor of ≳4. At higher positron/electron energies this ratio essentially decreases to ≈1.25, characteristic of the CR source.

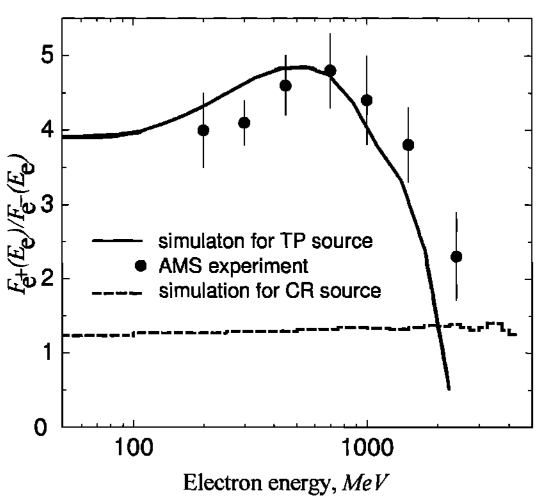

Figure 2. The simulated and experimental differential flux ratio of positrons to electrons, $F_{e^+}(E_e)/F_{e^-}(E_e)$, versus electron energy. TP, trapped proton. AMS, Alpha Magnetic Spectrometer; CR, cosmic ray.

Our estimates show that any contribution from the CR source to the positron and electron flux production from nuclear processes in the inner radiation zone of the Earth is relatively small compared to the TP source. Regarding the absolute electron and positron flux levels, the estimated positron flux with kinetic energies >100 MeV produced by TP at $L = 1.2$ is of the order of 500 m^{-2} s^{-1} sr^{-1} whereas the CR source may produce ~50–70 m^{-2} s^{-1} sr^{-1} electrons and positrons [i.e., *Pugacheva et al.*, 1997].

3. Discussion

We here compare the estimates obtained in section 2 to in situ observations on board the Russian Cosmos-1669 satellite and the Mir space station and with the recent results from space shuttle AMS experiment. The possible existence of the positron radiation belt theoretically considered in earlier works is essentially supported by the AMS experiment recently carried out on board the space shuttle *Discovery* at an orbit altitude of ~400 km [*AMS collaboration*, 1999]. This experiment has detected a strong presence of quasi-trapped positrons (called by authors as "long-lived" particles) with energies of 150–3000 MeV in the equatorial region at $L = 1.0$–1.3 with the mean flux ratio of positrons to electrons of 4.27 ± 0.17. The energy dependence of the e^+/e^- flux ratio observed is shown in Figure 2. These ratios are found to be in good agreement with the results of our numerical modeling for the e^+/e^- flux ratio at $E_e > 150$ MeV. At higher geomagnetic latitudes, corresponding to $L > 1.3$, the observed positron excess decreased to 1.28 ± 0.16, i.e., to the value characteristic of the CR source. We may reasonably conclude from this agreement that the positron excess observed in the AMS experiment around $L = 1.2$ is related to the local pion production by low-energy trapped protons in this region.

The positron fluxes observed by AMS at $L < 1.3$ demonstrate the "inverse" latitude dependence (i.e., a positron flux decrease with latitude) opposite to that expected for the albedo fluxes of CR origin. This "inverse" dependence is also evidence of the presence of an additional local positron source, different from the CR source. The same effect for >80 MeV quasi-trapped electron fluxes was clearly observed on board Cosmos-490 satellite with a device which did not distinguish between electrons and positrons [*Basilova et al.*, 1973]. Now, from the AMS observations we could suppose that "inverse" latitude dependence is provided mainly by the positron production.

The AMS instrument also looked at the distribution of hundreds of MeV helium nuclei, but only the ^3He isotope was observed. This is possible to understand in terms of quasi-elastic knockouts of secondary nuclei caused by protons of TP energies [*Komarov*, 1974]. In these specific reactions the secondaries of hundreds of MeV energies have a greater yield for the lighter ion species. The relative yield of D:^3He:^4He is expected to be 4100:33:1, and thus with overwhelming ^3He ion flux compared to the ^4He ion flux. Therefore the results of the ^3He observations also demonstrate that the nuclear interactions of TPs with the residual atmosphere can generate significant, detectable charged particle fluxes. This further supports the hypothesis of positron radiation belt production in the local nuclear reactions of TPs.

The Cosmos-1669 and the Mir experiments have emphasized their results at ≈400 km altitudes in terms of trapped particle observations in the BMA region and also of atmospheric albedo particles below the main radiation belt. The experiment on Cosmos-1669 shows a greater positron flux in 20–150 MeV energy range within the BMA region (≈250 m^{-2} s^{-1} sr^{-1}) compared to the fluxes detected outside of the radiation belt in the equatorial region (≈86 m^{-2} s^{-1} sr^{-1}) by a factor of ≈3. It means that an additional source of positrons has to exist in BMA, because the CR source provides the same positron fluxes both within and outside of BMA [*Gusev and Pugacheva*, 1982]. Consequently, this supports and agrees with the hypothesis of a viable local nuclear source for the positron radiation belt from energetic TPs. The experimental statistical uncertainties in this Cosmos-1669 experiment are, however, too large to make an entirely firm final conclusion based on this experiment alone. Further data provided by a similar instrument on board the Mir space station revealed an excess of electrons over positrons by factor ≈3 [*Galper et al.*, 1997] in the confinement region unlike our prevision of positron excess. Most likely, this experimental result can be accounted for by the rather large L shell range ($L = 1.2$–1.5) of averaging of the experimental data in comparison with the narrow confinement range of the simulation (a geomagnetic equator of field line $L = 1.2 \pm 0.1$ in our simulation). Because of that experimental L shell averaging, the finer details revealing generation properties become smeared out.

In fact, in the series of earlier Russian satellite measurements [*Basilova et al.*, 1982; *Nikolskij et al.*, 1984; *Galper et al.*, 1997, and references therein] the existence of a high-energy electron inner radiation belt was established. These electrons of energies 20–1000 MeV are found to exhibit a relatively narrow confinement region with a flux maximum at $L = 1.5$ and with a radial spread within $L = 1.25$–1.8, and thus an averaging of the results of positron measurements in the large L shell range of $L = 1.2$–1.5 (when at $L = 1.5$, a maximum of diffusive origin electrons is located) could easily lead to a "contamination" of the detailed e^+/e^- flux ratio by the other electron population. The AMS observation also shows a greater positron excess for $L \leq 1.3$. The Mir space station result is therefore not directly comparable to the very narrow confinement range of the simulation.

For electrons of energies <100 MeV and at $L = 1.2$ it may be of interest to evaluate the contribution from the radial diffusion mechanism as it could decrease the $F_{e^+}(E_e)/F_{e^-}(E_e)$ ratio considered from the nuclear collision source mechanism alone. We would also like to note that it is rather unreasonable to expect the existence of both trapped positrons and electrons of hundreds of MeV of pure radial diffusive origin in the innermost part of the Earth's magnetosphere. Indeed, it was earlier shown [*Pugacheva et al.*, 1998] that hundreds of MeV electrons cannot steadily diffuse down to $L \approx 1.2$ from the outer boundary of the magnetosphere without large energy losses. This potential radial influx is largely prohibited (or at least strongly discriminated against) owing to synchrotron radiation energy losses, since the cross-field transport timescales are much too long at very low L shells. We therefore conclude that in the hundreds of MeV energy range, in the innermost radiation belt, we expect the flux ratio, $F_{e^+}(E_e)/F_{e^-}(E_e)$, to be governed by the nuclear collision reactions.

4. Conclusion

Nuclear interactions of trapped protons of energies >300 MeV with upper atmosphere constituents are considered for the production of positrons in excess over electrons in the innermost magnetosphere. The numerical simulations performed in this work predict the existence of a positron belt in a narrow region around $L = 1.2$. The flux ratio of e^+/e^- is estimated to be ≈4 for energies of 40–1500 MeV. On the other hand, the effects of cosmic ray protons in the same spatial region provide e^+/e^- ratio near unity.

The AMS experiment carried out on board the space shuttle reported an excess of positrons over electrons by a factor of ≈4 at energies >200 MeV, with an energy dependence similar to the one predicted above, in the equatorial region of $L < 1.3$. This crucial observation offers strong support to the positron excess hypothesis presented herein.

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