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Secondary electrons and positrons in near earth orbit

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Abstract: The secondary e^+ and e^- populations in near earth orbit have been calculated by simulation. The results are in very good agreement with the recent AMS measurements. The e^+ over e^- flux ratio for particles below the geomagnetic cutoff appears to be due to the geomagnetic East-West effect.

The study of particle populations in the earth environment has been a field of intense research activity for more than 50 years [1]. After a period of latence, the field is regaining some interest with the occurence of a new generation of ambitious experimental projects which should bring major improvements to the instrumental accuracy of the measurements, and orders of magnitudes to the statistics of counting, with respect to previous experiments (see the references quoted in [2, 3] for the current and historical context). Some new measurements of particle flux close to earth have been performed recently by the AMS experiment, providing a large sample of such new data. These measurements open new prospects for high precision studies of the cosmic ray (CR)-atmosphere interactions, and of the dynamics of particles in the magnetosphere. This is of particular importance for the atmospheric neutrino issue, in the current context of this research field, since the knowledge of the (electron and muon) neutrino flux produced in the decay chain of pions in the atmosphere, is necessary for interpretating the results of the underground neutrino experiments [4]. Consequently, a good understanding of the associated electron and positron flux is highly relevant to this problem, these particles being produced in the same decay chain.

The proton distributions measured below the earth geomagnetic cutoff (GC) by AMS [2], have been successfully interpreted recently, in terms of interactions of the (proton) cosmic ray (CR) flux with the atmosphere [5]. This work is referred to as I in the following. Extending the work reported in I on protons, the present paper addresses the interpretation of the flux of positrons and electrons measured by AMS below the cutoff (subGC) [3], in the same phenomenological framework.

The lepton distributions observed by AMS, showed a few remarkable features, the main two of which are the following. First, the kinetic energy spectra have a strong subGC (then secondary) component (figure 1), similar to those observed in the proton flux. Second, the ratio of the e^+ over e^- flux is large in the equatorial region (≈ 4), and decreasing towards higher latitudes (≈ 1). The measured spectra extended from the kinetic energy threshold of the spectrometer at $\approx$0.15 GeV, up to about 30 GeV for e^- and 3 GeV for e^+. At low energy, the subGC secondary spectral yield decreases rapidly from a maximum around the low energy limit of the spectrometer, up to the GC energy, around 15 GeV/c for equatorial latitudes (electrons), where the high energy tail of the subGC component merges with the galactic CR spectrum above GC (figure 1). It is interesting to note that the subGC lepton and proton distributions at low latitudes have strikingly similar shapes [2, 3]. This indicates that the two populations could also have similar dynamical origins, providing a further motivation to investigate the lepton populations along the same lines as in I.

The observed subGC leptons are expected to originate mainly from pion production. The decay of charged pions produced in $p+A \rightarrow \pi + X$ (A atmospheric nuclei) collisions is expected to be dominant. The pair conversion of gammas, either decaying from neutral pions produced in the same reactions, or radiated by electron Bremstrahlung could also provide a significant contribution. The observed charge asymmetry of the electron-positron yield could be induced by the well known East-West (EW) geomagnetic effect [7] due to the earth magnetic (dipole) field. The latter consists of an EW angle dependence of the GC momentum, which is maximum one side and minimum at the opposite for a given charge of the particle, and conversely for the other charge (see below). The difference of production cross sections for π^+ and π^-, which is large at low incident proton energies [8] (see [9] for $pp \rightarrow \pi + X$ asymmetry), could also generate the observed effect. It could also result from a combination of both effects.

The study undertaken with the above ideas in mind, was based on the same Monte-Carlo simulation program for the lepton production and propagation, as used for protons in I (see this reference for details). For the present study, the pion production cross sections in $p + A$ collisions, the subsequent decays $\pi \rightarrow \mu \rightarrow e$ and $\pi_0 \rightarrow \gamma\gamma$, lepton Bremstrahlung and pair conversion cross sections, have been included in the computation program together with some technical improvements in the event processing. Incident CRs (p, e^+, e^-) are generated according to their natural abundance using the recent AMS measurements [3, 10]. They are propagated in the earth magnetic field and atmosphere, and allowed to interact with atmospheric nuclei. Each interaction can produce nucleons and pions according to their respective production cross sections and multiplicities. Each produced particle is then processed the same way, leading to the possible development of atmospheric cascades, in which each particle history is traced and recorded. The e^+ and e^- populations are generated by counting particles each time they cross upward or downward the mean altitude of AMS (370 km) within the detector acceptance (upwards and downwards particles are equivalent to splash-Albedo and secondary plus reentrant+Albedo particles in the Geophysics terminology, respectively).

The pion production cross-sections on atmospheric nuclei are a critical input to the calculations since they are expected to govern the observed lepton populations. For this reason, the event generator has been built to provide as accurately as possible these cross sections over the range of sensitivity of the measurements. The latter extends from a few hundred MeV/c above threshold on the low energy side, up to a few hundred GeV/c at high energy, where the sensitivity vanishes with the spectral distribution of the cosmic flux which varies like $\approx E^{-2.7}$ [6, 10]. The maximum of sensitivity is expected around 10 GeV. A set of experimental angular distributions of inclusive cross sections for proton induced charged pion production, measured around this latter energy [11, 12] could be well fitted by means of available parametrizations [15, 16]. However, the very broad incident energy range to be covered here required the functional form used, to be modified. Good results could be obtained between 0.73 GeV and 200 GeV incident kinetic energies [17] using the data from [8, 11, 12, 13]. A set of lower energy data were used [14] to constrain the energy dependence of the integrated cross section close to threshold. The

π^0 production cross section used was the mean value of π^+ and π^- cross sections, in agreement with [18], since no detailed data could be found.

The simulation program was run for $2{\cdot}10^7$ events reaching the earth. Note that statistics is limited by the very computer-time consuming processing of trapped low energy particles. The proton distributions obtained here (not shown) are in similar, even better at low energy, agreement with the data as reported in I. Figure 1 shows the e^+ and e^- downward spectra measured by AMS [3] compared to the results of the simulation, below and above GC, for the same geomagnetic latitudes. The two subGC lepton populations are seen to be very well reproduced in the equatorial region as well as at intermediate latitudes, whereas in the polar region, the simulated flux somewhat underestimates the experimental flux of secondaries. Note that at this latitude where the GC is very low, the latter is a most difficult spectrum to account for, since the cosmic proton energy range covers the whole domain from the threshold region up to the upper energy limit mentionned above. The neutral pion contributions are also shown on the figure. They have the same shape as for charged pions, and their overall contribution amounts to 17%(22%) of the total positron(electron) yield, whereas the Bremstrahlung contribution is 9%(15%). Note that the calculated distributions are entirely determined by the physics input of the simulation without any adjustable parameter. A similar agreement is obtained for upward e^+ and e^- spectra (not shown). As it was found for protons in I, the low energy flux obtained for e^+ and e^- in the equatorial region is mainly due to trapped particles, which are in fact produced with a rather low probability. Their large contribution is due essentially to their high crossing multiplicity of the detection altitude. Long simulation runs are required for significant statistics of such events to be produced.

Upper figure 2 shows the experimental and simulated (with 1 σ statistical error bars) ratios of the e^+ over e^- energy-integrated yields as a function of the geomagnetic latitude. The agreement is good, within 1-2 σ, for all data points. A simulation run has been made with the π^+ production cross section taken equal to the π^- one. In this case the asymmetry obtained is the same as for the normal calculation, to within statistical errors. The charge asymmetry of the π production cross section then has a minor, if any, contribution to the observed lepton asymmetry.

Now, let the EW angle be defined as the angle between particle momentum and meridian plane in geographical coordinates ($+\frac{\pi}{2}$ for E-bound particles). Lower figure 2 shows the EW angle distributions of the lepton-producing particle momenta at the interaction point in the equatorial (upper) and high latitude (lower) regions (see latitude bin values on the figure). It shows very clearly that the e^+ and e^- populations around the equator, are generated by (mostly proton) particle momenta quasi exclusively oriented eastward for e^+ and westward for e^-, the e^+ overall flux being more than 3 times larger than the e^- flux, whereas at high latitudes, the EW asymmetry is much weaker and the flux are about equal. This asymmetry originates from the well known GC dependence on the EW angle and results in the lepton charge asymmetry observed, because of the following specific conditions:

1. This EW angle dependence consists of a GC momentum P_{GC} much lower for E-bound (P^E_{GC} ≈11 GeV/c) than for W-bound (P^W_{GC} ≈60 GeV/c) protons [7]. Consequently, a much larger flux of E-bound protons is allowed to interact in the atmosphere, since the incident flux decreases rapidly with the particle momentum as $E^{-2.7}$, E being the particle energy [6].

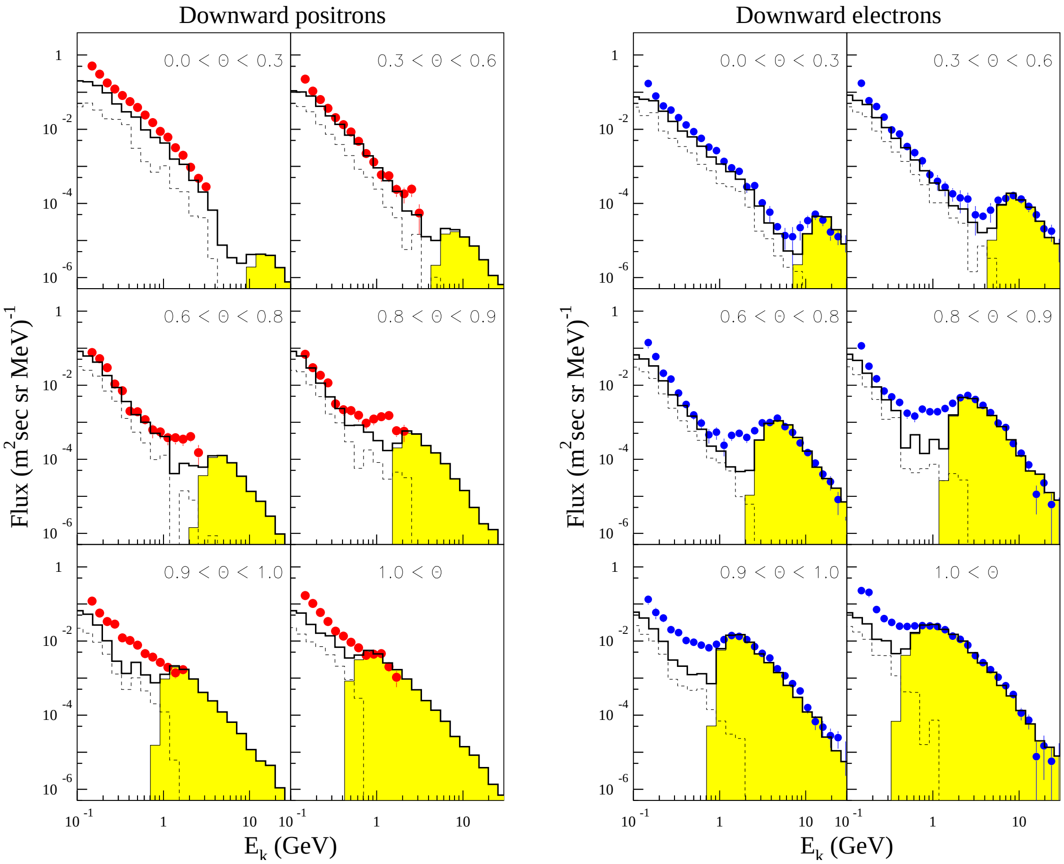

Figure 1: *Simulated kinetic energy spectra for* e^+ *and* e^- *(histograms), compared to the AMS data (full circles) in bins of geomagnetic latitude. The histograms correspond to the primary cosmic (shaded), and total (thick solid) flux respectively. The dashed histograms show the contribution of pair conversion from gammas originating from neutral-pion decay and electron/positron Bremstrahlung.*

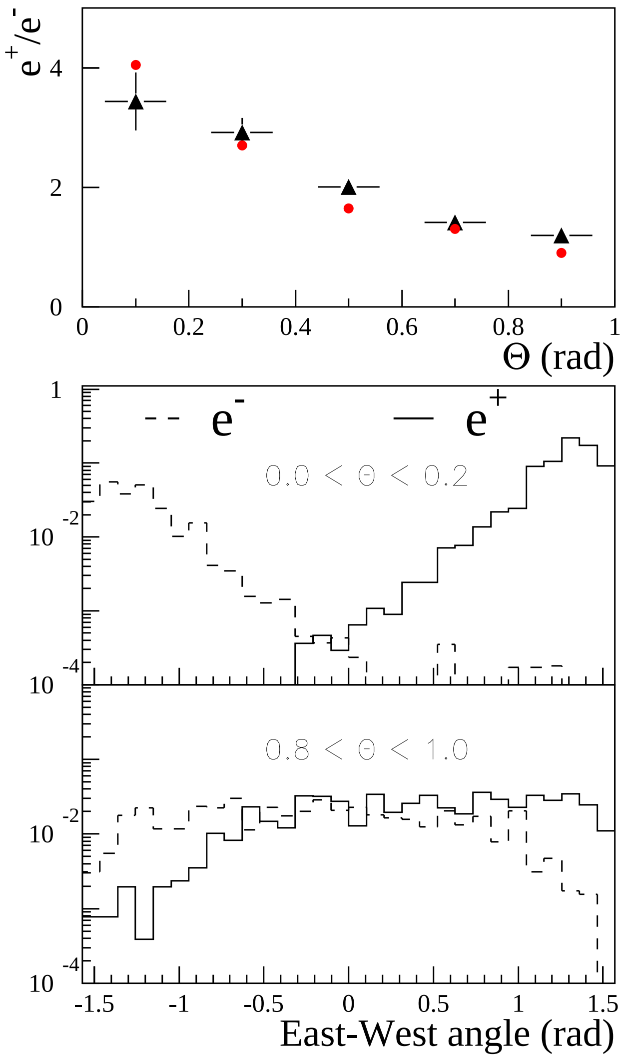

Figure 2: *Top: e^+/e^- flux ratio obtained from this work (triangles), compared to the AMS data (full circle) as a function of the geomagnetic latitude. Middle: EW angle distributions of the incident protons having generated a secondary lepton at the interaction point, for the equatorial latitude bin. Bottom: Same for a high latitude bin. The histograms are normalized to the sum of channels equals 1.*

2. The π production cross section is peaked at forward angles, and this direction is approximately conserved through the decay process (for electrons/positrons above 0.2 GeV). The produced leptons then have about the same direction as incident (proton) particles. The proton flux asymmetry then translates into a lepton flux asymmetry through this direction conserving effect.

3. The acceptance of the earth-magnetosphere system is larger for E-bound than for W-bound secondary positrons, and conversely for electrons. Qualitatively, this is because any particle bent up by the earth magnetic field will propagate outside the atmosphere, whereas if bent down it will be absorbed with a high probability in the atmosphere. Therefore (E-bound) protons will produce a larger flux of (bent up) positrons.

The above three conditions are required for the observed asymmetry to exist. For example, a forward-backward symmetric lepton production would wash out the observed effect. Note that the sign of the asymmetry would change with the sign of the incident CR particles.

This effect decreases progressively with the increasing latitudes because of the decreasing EW difference of P_{GC}. It is expected to vanish at the poles.

These results confirm the qualitative estimate from [19], made on the basis of assumptions in agreement with our conclusions. See also [20].

The contributions of the other CR components, ^4He, ^{12}C, ^{16}O, etc.., should scale roughly with their respective flux, with some enhancement due to the larger total reaction cross sections however. It is then expected to be of the order of 10-20% of the proton yield, i.e., within the fringe of uncertainty of the analysis. This is being evaluated quantitatively for ^4He.

In conclusion, it has been shown that the e^+ and e^- populations measured by AMS below the geomagnetic cutoff can be well reproduced by a simulation assuming they originate from the hadronic production of π^+ and π^- in proton collisions with atmospheric nuclei. The asymmetry of populations observed for e^+ and e^- is due to a combination of: East-West asymmetry of the geomagnetic cutoff, forward peaking of the production cross section, and atmospheric absorption of the produced leptons. This conclusion could be reached on the basis of the good agreement between experimental data and simulation results. The difference between the π^+ and π^- production cross sections plays a minor role in the phenomenon.

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