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In considering the process $p + p \rightarrow 2\,N + n\pi;\ \pi^{\pm} \rightarrow \mu^{\pm} + \nu\ ;$ $\mu^{\pm} \rightarrow e^{\pm} + 2\nu$ as a source of cosmic-ray electrons, most authors[1,2,3] have made the reasonable assumption that at high energies one would observe the ratio $N(e^{+})/N(e^{-}) \approx 1$. This assumption is based on the idea that charge conservation limits the excess of positively charged secondaries arising from any collision to be, at most, two. The high multiplicity of secondaries arising from many GeV collisions then tends to wash out this excess leading to approximate equality of the numbers of positively and negatively charged electrons. There is also the implicit, but rarely mentioned, assumption that a given observed electron constitutes a <u>random</u> sample of the secondaries from a particular high energy collision. It is the purpose of this note to point out that this assumption is probably not true and that at high energies the ratio $N(e^{+})/N(e^{-})$ will be considerably larger than one.

In a previous paper[3] (hereafter called I) I pointed out that if "Excited isobars" [4,5] play a role in high-energy, cosmic-ray nucleon-nucleon collisions the probability that a given secondary came from the decay of the isobar rather than from some sort of "fireball" goes to unity as the energy of the secondary increases. There is now considerable evidence[6,8] that there are isobars excited in collisions up to 23 GeV/c[9] primary momentum and that retention of a fixed fraction of the initial energy by the primary particle holds true for very high energies ($\sim 10^{16}$ eV) and for as many as ten collisions in succession.[10] Furthermore, it appears evident that as one goes to higher energies the well known $\left(\frac{3}{2}, \frac{3}{2}\right)$ isobar fades out of the picture and the excitation of isobars proceeds with no exchange of isospin or strangeness;[6,9] in other words, the isobars excited in a p, p collision are all of the $T = \frac{1}{2}$, $T_3 = \frac{1}{2}$, non-strange variety at $\sim 23$ GeV/c. Since the decay of such isobars is via the strong interactions and hence isotopic spin conserving this severely constrains the charge ratio of the resulting secondaries. We shall derive an estimate for the value of this ratio at high energies based on the above considerations.

If we assume that in a high energy p, p collision both nucleons are excited to a mass $M_B$ with a certain fraction $\delta$ of the COM energy going into producing mesons via a pionization ("fireball") mechanism, from equation (11b) of I we see that the lab-energy of the forward going isobar is approximately given by

$$\gamma_B \approx \gamma_p/\gamma_m \qquad \text{where} \qquad \gamma = \frac{E}{Mc^2}$$

$$\text{and} \qquad \gamma_m = \frac{M_B}{M_p\,(1 - \delta)} \; . \tag{1}$$

If the primary protons have a differential energy spectrum of the form $k\,\gamma_p^{\,-\alpha}$ the production spectrum of isobars will be given by

$$\left(k' \;\; \gamma_m^{\,1-\alpha}\right) \gamma_B^{\;-\alpha} \; .$$

If the isobar now decays to produce secondary particles which have differential energy spectra in the isobar COM frame $f_i^*\,(\gamma_i^*)$ which are bounded in energy $\left(f_i^*\,(\gamma_i^*) = 0 \text{ for } \gamma_i^* > B_i\right)$ we see from equation (8) of I that the secondaries will have lab frame spectra $f_i(\gamma_i)$ for $\gamma_i \gg B_i$ given by

$$f_i\;(\gamma_i)\;d\gamma_i \;=\; K_i\left(k'\gamma_m^{\;1-\alpha}\right)\gamma_i^{\;-\alpha}\;d\gamma_i$$

where

$$K_i = \int_1^{B_i} \frac{f_i^*(\gamma_i^*)}{\alpha} \left[ \frac{(Z_i^+)^\alpha - (Z_i^-)^\alpha}{Z_i^+ - Z_i^-} \right] d\gamma_i^* \qquad (2)$$

and $Z^\pm = \gamma_i^* \pm \left(\gamma_i^{*2} - 1\right)^{\frac{1}{2}}$

Further decays of these particles will reproduce the same spectra with the further multiplication of a factor $K_j$ computed in a manner identical to expression (2). Since the final spectra of electrons, both positive and negative, will be of the form $\gamma^{-\alpha}\, d\gamma$ the charge ratio at any energy (high enough for the asymptotic formulas to apply; ≥ 1 GeV) will be found simply by taking the ratio of the appropriate factor, computed by following the various decay chains leading to $e^+$ and $e^-$ and forming the products $K_i\, K_j\, K_e$ - - - etc.

In 2 body decays the functions $f_i^*$ will be delta functions about a characteristic value of $\gamma_i^*$. For n body decays with $n \geq 3$

the functions $f_i^*$ will be real functions, however, we shall approximate these too by delta functions about some average value $\langle \gamma_i^* \rangle$ .
By rights we should follow the chain involving neutrons since they are unstable and produce $e^-$, however, the kinematic factor for neutron decay $K_{n \to e} \approx 3.1$ which $K_{\pi \to \mu \to e} \approx 740$ showing that the contribution from neutrons is insignificant compared to that from pions.
An isobar with $T = \frac{1}{2}$, $T_3 = \frac{1}{2}$ will decay about 80%[11] of the time via one pion decay into the state $\left[ \sqrt{\frac{2}{3}}\ \pi^+ n - \sqrt{\frac{1}{3}}\ \pi^0 p \right]$ and about 20%[11] of the time via two pion decay into the state

$\left[ A\, \epsilon\, p + B \left( \sqrt{\frac{2}{3}}\ \rho^+ n - \sqrt{\frac{1}{3}}\, \rho^0 p \right) \right]$ where A is the amplitude for

the two pion T = 0 state; $\epsilon = \sqrt{\frac{1}{3}} \left( \pi^+ \pi^- + \pi^- \pi^+ - \pi^0 \pi^0 \right)$

and B is the amplitude for the two pion T = 1 state;

$$\rho^+ = 1/\sqrt{2}\ (\pi^+ \pi^0 - \pi^0 \pi^+)$$

$$\rho^0 = 1/\sqrt{2}\ (\pi^+ \pi^- - \pi^- \pi^+)$$

$$\rho^- = 1/\sqrt{2}\ (\pi^0 \pi^- - \pi^- \pi^0)$$

In order to calculate the $K_\pi^+$ and $K_\pi^-$ factors we must know the values for the amplitudes A and B and the mass $M_B$ of the isobar involved. Experiment[9] indicates that the 1688 MeV $N^*$ is the one that dominates collisions at 23 GeV/c and we shall assume this to be true at higher energies as well. Both experiment[12] and theory[13] indicate that the 1688 MeV resonance is strongly associated with the pion-pion resonance in the T = 1 or ρ state (the ρ or vector meson) so we shall make the choice $A = 0$, $|B| = 1$. This choice leads to $\langle\gamma_\pi^*\rangle = 4.22$ for one pion decay and $\langle\gamma_\pi^*\rangle = 2.45$ for two pion decay and $K_\pi = 9.6$ and $K_\pi = 4.23$ for the two cases respectively choosing the cosmic ray spectrum exponent $\alpha = 2.5$. Combining the one and two pion decay cases one obtains

$$K_\pi^+ = (.8)\left(\frac{2}{3}\right)(9.6) + (.2)\ (4.23) = 6.0$$

$$K_\pi^- = (.2)\left(\frac{1}{3}\right)(4.23) = 0.284$$

and $\quad K_\pi^+/K_\pi^- = 21$

The factor $K_{\pi \to \mu \to e}$ multiplies top and bottom so the final ratio $K_e^{+}/K_e^{-}$ is also equal to 21.

We see that this is a good bit larger than one as has been previously supposed and although changes in the model such as including other isobars of higher or lower mass and choices other than $A = 0$, $|B| = 1$ will alter these results somewhat, we do not expect the overall conclusions of this note to be significantly changed.

This result may be compared with the one measurement[14] made in the asymptotic energy range (1 - 3 GeV) of the cosmic-ray electron charge ratio; $N(e^{+})/N(e^{-}) \leqq 0.49 \begin{smallmatrix} +.47 \\ -.26 \end{smallmatrix}$ . Combining this with our result we may say that no more than about a third of the electrons were of a secondary nature since we may consider essentially all of the $e^{-}$ as coming from some primary acceleration process.

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