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Cosmic Radiation, Production of Antimatter and Their Implications.

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Summary. — The puzzles connected with the observation of a large $\bar{p}/p$ ratio, the measured rising ratio of e^+/e^- and some other unsolved, important problems led some theorists to conceive of the extra-galactic origin of cosmic rays and to postulate the existence of the antigalaxies. We have attempted here to understand the problems on the basis of the simple leaky box model (SLBM) with one particular phenomenological model for particle production, and some very recent observational features of high-energy collisions that call for theoretical attention. The conclusion is: the agreements are still not satisfactory if we accept and adhere to the correctness of the previous data. In recent times there has been a dramatic change in the situation with regard to this discrepancy. The latest data have just been taken note of but the conclusions are arrived at here more on the basis of the earlier data than on the recent ones as they necessitate further confirmation.

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1. – Introduction.

The ratio of antiproton to proton flux is of much interest from both cosmic-ray physics and particle physics point of view. One very recent experiment [1] has developed a resurgence of interest in this field [2].

In the recent past Basini *et al.* [3] proposed an experiment to search for antimatter and to investigate the open question of matter-antimatter symmetry by space spectrometer. They emphasized the need for continuing such experiments to settle the controversial questions related with cosmological models, propagational characteristics of cosmic rays and properties of excess production of some antiparticle secondaries.

But, very recently, there has been a significant change in the situation with regard to the excess production of the antiproton secondaries at lower energies. In fact Ahlen *et al.* [1] have reported the upper limit to the $\bar{p}/p$ ratio a magnitude $\sim 4.6 \cdot 10^{-5}$ at the 85% confidence limit (CL) at the top of the atmosphere and for antiprotons of low energy. Another US group [2c] has also given a corrected and

The positrons are obtained through the decay $\pi^+ \to \mu^+ \to e^+$ (positron). Thus the resulting positron spectrum (for positron energies in excess of a few GeV) is

$$(4) \qquad J_{e^+}(E) = \frac{2(\tau+6)}{(\tau+1)(\tau+3)(\tau+4)} \left(\frac{m_\mu}{m_\pi}\right)^\tau \frac{Am(E)}{m_p} \int_E^\infty \frac{d\sigma_{\pi^+}}{dE}(E, E_p) E_p^{-(\tau+1)} dE_p \,,$$

where $m(E)$ is the mean path length of interstellar hydrogen traversed in g/cm^2, m_p is the proton mass in g, $(d\sigma_{\bar{p}}/dE)(E, E_p)$ is the cross-section in cm^2 for producing an antiproton of energy E in the collision of a proton of energy E_p with an interstellar hydrogen nucleus and $J_p(E_p)$ is the primary proton spectrum. The factor 2 in expression (1) is due to the assumptions that antineutron equals antiproton production and that all antineutrons decay. The choice of the value of A depends on our selection of the nature of the proton spectrum on which we shall focus in the next section.

3. – Method of calculations.

3·1. *Choice of the spectrum.* – We shall use here the latest JACEE spectrum [12] as it presents the fit at highest experimental energies. In the primary proton energy range from 10^2 GeV/nucleon to $5 \cdot 10^6$ GeV/nucleon, the differential energy spectrum is assumed to have a shape of

$$1.87 E_p^{-2.7} (\text{cm}^2 \, \text{s sr GeV/nucleus})^{-1}$$

So in practice for this energy range $\tau = 1.7$ and $A = 1.87$. Although for higher energies the prescribed JACEE spectrum is a bit different.

3·2. *Effect of nuclear collisions.* – The cross-sections are taken here for both $pp \to \bar{p} + \text{anything}$ and $p + \text{light nucleus} \to \bar{p} + \text{anything}$ and the latter has been converted to expectation for pp. The A-dependence of hadron-nucleus collision is inserted in the manner of Minorikawa and Missui [13]:

$$(5) \qquad E\frac{d^3\sigma}{dp^3}(hA \to cX) = E\frac{d^3\sigma_h}{dp^3}(hP \to cX)\, \eta_h^c(y, P_T) \exp[\alpha_h^c(y, p_T) \ln A] \,.$$

From some previous works of Takagi [14] and Caroll *et al.* [15] we can arrive at an acceptable relation $(\sigma_{hp}/\sigma_h^0)\, \eta_h^c = 1.25 \div 1.5$ which helps in evaluating $\eta_h^c\,(y, p_T)$. The contributions from αp and $\alpha\alpha$ collisions [16] at high energies will be taken into consideration. In cosmic-ray physics some other collisions also are of paramount importance which are, in the main, pion-proton (hydrogen) or pion-nucleus collisions. The contributions from them have so far not been taken into account in the estimation of the $\bar{p}/p$ ratio. We would like to take the effects of these collisions into our consideration on the basis of the contention by Shabelskii [17] that the inclusive spectrum of all charged particles are approximately the same in proton-proton and pion-proton collisions at least upto 10^6 GeV^2 and the contention that violation of Feynman scaling is weaker in πp collisions than in pp scattering at high energies.

considerably reduced value of the $\bar{p}/p$ ratio for very low-energy antiprotons. Surely we take note of these results here but we can in no way consider them to be final. Further experimental results are awaited for any final conclusion about this very controversial issue.

The earlier measurements [4-6] of the cosmic-ray antiprotons reveal the fact that the ratio of antiprotons to protons would be much larger than the limit to antimatter fraction in the local group [7, 8]. The indications support the idea that the antiprotons in the cosmic rays might have had an extragalactic origin in the sense that the application of the standard models for particle production at very high energies does not provide any satisfactory explanation for these large antibaryon ratios. This might lead to the comment that antiprotons are radiated by antimatter galaxies and the universe is symmetric in matter-antimatter connection. Furthermore, Webber [9] and Muller and Tang [10, 11] reported that the e^+/e^- ratio shows a clear rising nature beyond 10 GeV which, according to them, appears to suggest one possibility that a primary component of positrons (antiparticles) becomes significant above 10 GeV and such a primary positron component could only come from the antigalaxies. Thus the behaviours of these ratios point apparently to the existence of some unknown sources of which one could be the proposed antigalaxy.

We would like to examine here the validity of such concepts very carefully and the probable realisability of such postulates as to the existence of the antigalaxies. We make this study here exclusively on the basis of the simple leaky box model (SLBM) for galactic propagation.

2. – Basic theoretical tools.

Starting from the inclusive antiproton production via proton-proton interaction

$$\mathrm{pp} \to \bar{\mathrm{p}} + \text{anything}$$

at laboratory energy threshold ~ 7 GeV for the incident proton, the differential antiproton spectrum [6] is given by

$$J_{\bar{\mathrm{p}}}(E) \simeq \frac{2m(E)}{m_{\mathrm{p}}} \int_E^{\infty} \frac{\mathrm{d}\sigma_{\bar{\mathrm{p}}}}{\mathrm{d}E}(E, E_{\mathrm{p}})\, J_{\mathrm{p}}(E_{\mathrm{p}})\, \mathrm{d}E_{\mathrm{p}} \tag{1}$$

and

$$\frac{J_{\bar{\mathrm{p}}}(E)}{J_{\mathrm{p}}(E)} \simeq \frac{2m(E)}{m_{\mathrm{p}}} \int_0^1 E\, \frac{\mathrm{d}\sigma_{\bar{\mathrm{p}}}}{\mathrm{d}E}(E, E/R)\, R^{\tau-1}\, \mathrm{d}R\,. \tag{2}$$

On the basis of the same fundamental equation of flux of secondary particles and on the basis of a chosen proton spectrum of the form $J_{\mathrm{p}}(E) = AE_{\mathrm{p}}^{-(\tau+1)}$ it can also be shown that

$$J_{\pi^+}(E) \simeq \frac{m(E)A}{m_{\mathrm{p}}} \int_E^{\infty} \frac{\mathrm{d}\sigma_{\pi^+}}{\mathrm{d}E}(E, E_{\mathrm{p}})\, E_{\mathrm{p}}^{-(\tau+1)}\, \mathrm{d}E_{\mathrm{p}}\,. \tag{3}$$

3·3. *Nature of inclusive cross-sections and acceptance of a very moderate violation of scaling.* – The nature of our choice of the empirical fits to the inclusive cross-sections proposed by Rossi *et al.* [18] relies on a very recent observation by Alner *et al.* [19] that the Feynman scaling at the highest SPS $p\bar{p}$ collider energy $S^{1/2} = 900$ GeV is quite valid in the central region and that there is a breaking of the Feynman scaling only in the fragmentation region by marginal amount of 10 to 20 percent. This can be taken care of with the help of the prescription of Wdowczyk and Wolfendale [20] which we accept and make use of despite the theoretical prediction of a larger violation of Feynman scaling by Cheung and MacKeown [21]. Before writing down the expressions for inclusive cross-sections in terms of the rapidity variable let us first define it in the Lorentz frame,

$$y^{\text{c.m.}} = \frac{1}{2}\ln\left[(E + p_{\text{L}})/(E - p_{\text{L}})\right]$$

with the conversion factor

$$y^{\text{lab}} = y^{\text{c.m.}} + \ln\left[\bar{\alpha}(1 + \bar{\beta})\right],$$

where $\bar{\alpha}$ is the Lorentz factor of c.m. system and $[\ln\bar{\alpha}(1 + \bar{\beta})]$ is the rapidity of the incident particle in the c.m. system. This is the additive property of rapidity.

In terms of (S, y, p_{T})

$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3} = f(S, y, p_{\text{T}})\,. \tag{6}$$

At very high energies by using the property of factorization the above might be written on the basis of the violation of the Feynman scaling *à la* Wdowczyk and Wolfendale [22, 23] in the following manner:

$$f(y, p_{\text{T}}) = g\left[y\left(\frac{S}{S_0}\right)^{\varepsilon}\right]h\left[p_{\text{T}}\left(\frac{S}{S}\right)^{\varepsilon}\right] = g'(y)\,h'(p_{\text{T}})\,, \tag{7}$$

where the term $(S/S_0)^{\varepsilon}$ represents the moderate violation of scaling with $\varepsilon = 0.15$ and $S_0 = 100\ \text{GeV}^2$.

The nature of dependences of the inclusive cross-sections on transverse momenta is taken from Rossi *et al.* [18] as were done by Ganguly and Sreekantan [16]:

$$h'(p_{\text{T}}) = \exp\left[-bp_{\text{T}}\right], \tag{8}$$

with

$$b_{\pi^+} = 6.5\ (\text{GeV/c})^{-1}\,, \qquad \text{b}_{\pi^-} = 7.0\ (\text{GeV/c})^{-1}\,, \tag{9}$$

and

$$b_{\bar{\text{p}}\text{-secondary}} = b_{\text{p-secondary}} = 4.0\ (\text{GeV/c})^{-1}\,.$$

The nature of rapidity dependence is also taken in a manner similar to Ganguli and Sreekantan:

$$g'(y) = A_1 \exp\left[-A_2 \Big/ \left(Z + y\left(\frac{S}{S_0}\right)^{\varepsilon}\right)^{\alpha}\right] + A_3 , \tag{10}$$

where Z is a constant $= 2$ for charged pions and $= 0$ for $\bar{\text{p}}$ distributions. The constants A_1, A_2 and A_3, α are given in table I.

TABLE I. – *Values of the fitted parameters to the rapidity distribution of charged pions and antiprotons.*

Particles produced	A_1	A_2	A_3	α
Negatively charged pion	250	75	0.04	4.00
Positively charged pion	185.8	200	4.5	5.25
Antiprotons, energy >200 GeV	6.8	5.2	0.0	1.75
Antiprotons, energy <20 GeV	3.5	4.8	0.0	1.25

The solid curves in fig. 2 and 3 depict the results of our theoretical calculations against the experimental background for antiprotons and positrons, respectively. The theoretical calculations necessitate the use of mean grammage for the interstellar space denoted by $\langle\lambda\rangle_s$. The experimental points in fig. 1 and 2 lead to different and moderately diverging values of $\langle\lambda\rangle$ and the mass composition analysis demands a different $\langle\lambda_N\rangle$ whose nature with changes of total energy presents a contrasting picture (fig. 1). This points to one weakness of the simple leaky box model

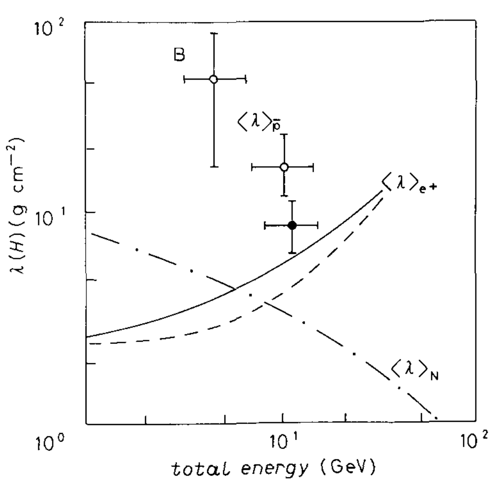

Fig. 1. – Plot of mean grammage *vs.* total energy for cosmic rays incident on interstellar hydrogen, derived using the leaky box model of cosmic-ray propagation. $\langle\lambda\rangle_{\bar{p}}$ is almost the same as that of ref. [26*b*]. There is a slight difference in the values of $\langle\lambda\rangle_{e^+}$ between the present calculations shown by the solid upward-moving curve and the results of Szabelski *et al.* [26*b*] represented by the dashed curve. The difference between the values of $\langle\lambda\rangle_{\bar{p}}$ and $\langle\lambda\rangle_N$ is normally attributed to the propagation effects.

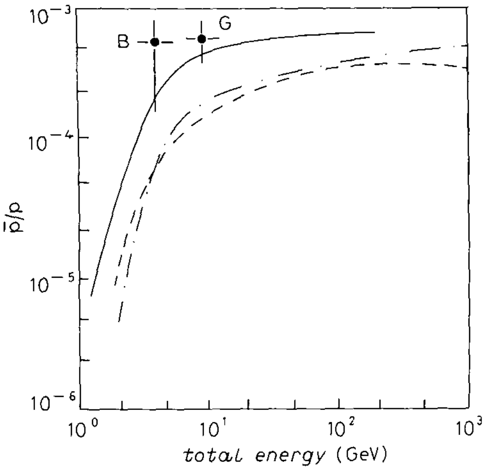

Fig. 2.

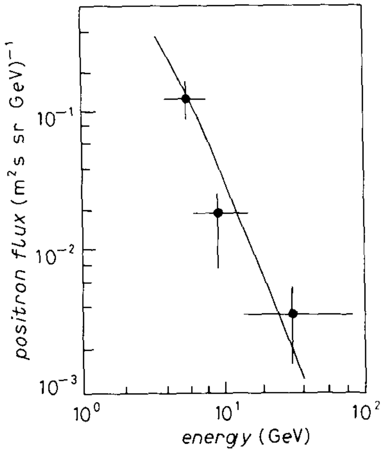

Fig. 3.

Fig. 2. – Comparison of observed and calculated ratios of antiprotons to protons in the primary cosmic-ray beam. G denotes the measurement of Golden *et al.* [5*a*] and B that of Bogomolov *et al.* [5*b*]. The estimations are based on 5 gm^{-2} of interstellar hydrogen traversed by the cosmic rays using the simple leaky box model (SLBM). The solid curve represents our model-based calculations. The dot-dashed curve indicates the results of calculations by Szabelski *et al.* [26*b*] and the simply dashed (or broken) curve that of Gaisser and Maurer [6*a*] with the value of gamma to be 2.6.

Fig. 3. – Positron flux *vs.* energy plot. Data points are from Bhadwar *et al.* [6] and the solid curve is the theoretical plot.

(SLBM). But our idea is that the use of a more realistic proton spectrum might reduce these uncertainties to a considerable extent.

The breaking of the Feynman scaling affects essentially the nature of the rise of the multiplicity. In other words, the multiplicity of the secondaries increases at a rate faster than that predicted by a logarithmic rise. This increases at high energies the population of both pions and other secondaries among which antiprotons constitute one variety. The more copious the production of positive pions, the larger will be the contribution to the positron flux. The ratio of $\bar{p}/p$ pertains to the secondary antiprotons and primary proton flux (and not secondary proton flux). So the comparatively higher values of $\bar{p}/p$ ratio and of positron flux at high energies depicted in fig. 2 and 3 seem to be quite reasonable with the small amount of scaling violation assumed in the present calculations. This apart, the use of the JACEE primary spectrum has had a bearing on the present theoretical results. We did not consider the effect of deceleration of particles when they have accummulated the bulk of their grammage on the $\bar{p}/p$ ratio or on the positron flux. This is for two reasons: one, the deceleration concept did never help explain the positron flux and, two, the deceleration idea has been played down in cosmic-ray physics phenomena as it gives rise to several other problems.

4. – Low-energy antiproton flux and the present model.

Although at extremely high energies it is true that the annihilation cross-section becomes really very negligible, at comparatively lower energies this is not the case.

Antiprotons then interact with matter leading to annihilation, charge exchange or depletion of energy [24]. The total inelastic cross-section for $\bar{p}$ includes annihilation and inelastic interactions leading to particle production and charge-exchange. The inelastic interactions involve the production of secondary particles which certainly cause attenuation of antiprotons and production of secondary antiprotons as well. But on the whole the annihilation channel has a diminutive effect on the magnitude of the single-particle inclusive cross-section.

Let us represent the invariant cross-section at low energy (LE) by $[E(d^3\sigma/dp^3)]_{LE}$ and the invariant cross-section with moderate violation of scaling (MVS) as $[E(d^3\sigma/dp^3)]_{MVS}$ at high energies in the following manner:

(11)
$$\frac{\left[E\dfrac{d^3\sigma}{dp^3}\right]_{MVS}}{\left[E\dfrac{d^3\sigma}{dp^3}\right]_{LE}} - 1 \simeq 6\cdot 10^{-3} f(Q)\,,$$

where $Q = \sqrt{S} - 4m_p^2$. The shape of $f(Q)$ has been used in the same way as has been predicted by Stephens [24] with the use of $X_F(S/S_0)^\varepsilon$ instead of X_R.

The use of the JACEE spectrum and the inclusion of this diminutive effect bring down the value of $\bar{p}/p$ ratio in fig. 4 which obviously falls short of the measured values with rigidity confinement coefficient $\delta = 0.6$ for galactic cosmic rays. This reduction within the framework of simple leaky box model (SLBM) makes the existence of antigalaxy more probable if we accept the correctness of the old, previous data. It must be understood that in the study of the behaviour of the $\bar{p}/p$ ratio, the low-energy values form the crux of the problem. And at low energies the large-p_T particles do not show up either at all or at least prominently in the production process. So the contribution from them does not arise here. The excess production, if any, thus could be attributed to some extragalactic source of antiprotons so far as our study with the simple leaky

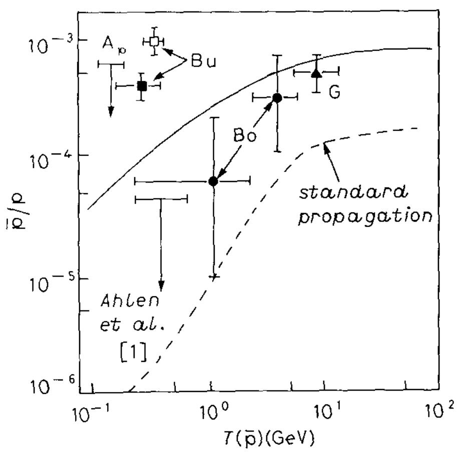

Fig. 4. – Plot of $\bar{p}/p$ ratio *vs.* energy of the antiprotons extending from very low-energy antiprotons to relatively high energies. The solid curve is our theoretical prediction based on the present calculation for the galactic rigidity coefficient, $\delta = 0.6$. Very recent data of Ahlen *et al.* [1] have also been shown with special emphasis.

box model (SLBM) is concerned. But this excess production has, by now, already been questioned by the experimentalists [1].

5. – Low-energy antiproton flux, antimatter and antigalaxy: the past scenario and the present confusion.

Although the high-energy behaviour of the $\bar{p}/p$ ratios leaves room for doubt about the existence of antigalaxies, its low-energy value, until very recently, pointed just the opposite: the existence of antimatter and of antigalaxies for that matter was a near certainty. Stecker *et al.* [25] argued that active galaxies can provide the bulk of the extragalactic cosmic-ray flux. This would lead to photo-disintegration of heavier nucleii and this very fact removed the difficulty of explaining the low ratio of antinuclei to nuclei in cosmic rays, while explaining the $\bar{p}/p$ ratio and the antiproton spectrum.

But the crucial test of existence of antimatter and antigalaxy lays in the verification of two factors: i) the clear detection of a predicted particle like antihelium nucleus would provide strong support to the extragalactic origin of a component of the cosmic rays [26] and ii) the unambiguous observation of the predicted rising $\bar{p}/p$ ratio with rigidity confinement given by the simple proportionality relation of $\bar{p}/p$ ratio $\sim R^{\delta}$ as was predicted by Stephens with $\delta = 0.6$, as is shown in fig. 4. Our estimated value on the basis of the model of Rossi *et al.* [18] and of Ganguly and Sreekantan [16] obviously gives us values of the $\bar{p}/p$ ratio higher than those reported in ref. [1]. This is not unexpected because we have inserted in our calculations all the standard high-energy assumptions, whereas the experimental results reported in ref. [1] and [2] are for extremely low-energy secondary antiprotons. In settling the controversy about the antimatter or antigalaxy one has to consider the excess production of the antielectrons and some other antinuclei at high energies.

6. – Concluding remarks.

While summing up let us, at the very beginning, leave aside the impact of the very recent experimental results [1]. The physical factors that emerged very clearly in the field of ultrahigh-energy physics have otherwise been taken into account in our analytical and numerical calculations of both the $\bar{p}/p$ ratio and the positron flux. What we have introduced here anew are i) the effect of a moderate violation of scaling in the dynamics of production of secondary particles in high-energy reactions; ii) the influence of the latest JACEE spectrum for primary protons; iii) the inclusion of A-dependence of cross-sections for both the nucleon and pion-induced high-energy reactions and iv) reckoning of the pion-induced high-energy collisions in the upper atmosphere. And all this has been incorporated within the framework of the simple leaky box model (SLBM) amongst many other models as described by Cesarsky [27]. Moreover, the agreement between the theoretical results and the experimental values is far from being satisfactory, although it is much better now than the earlier results, especially for the $\bar{p}/p$ ratio. The minor discrepancy that still persists at high antiproton energies might be ascribed effectively to three different reasons which should and must be eliminated one by one. The large value of the statistical uncertainty in the experimental measurement in cosmic-ray physics is almost an unavoidable factor for which we omit this aspect. The remaining three possible contributing factors are i) an additive contribution from the closed-galaxy type of model at most by 50% as proposed by Stephens [28, 29], ii) the contribution from the large-p_T inclusive production of hadrons as was shown by Bhattacharyya and Pal [30] and iii) an origin of antiprotons and of positrons or antielectrons from the hypothesized concept of the existence of antigalaxy. Of them, the first factor would come into the picture, if and only if the excess production of the antiprotons is confirmed contrary to the measurement by Ahlen *et al.* [1]. Obviously, this has now become very much doubtful. The behaviour of the low-energy antiproton production and, more specifically, the $\bar{p}/p$ ratio helps to eliminate the second factor stated above almost unambiguously. And within the framework of the originally proposed simple leaky box model (SLBM) the third factor, then, practically comes out to be the only choice for explaining any observed discrepancy for which further accurate experimental studies are needed on the behaviour of both the low-energy $\bar{p}/p$ ratios and high-energy e^+/e^- ratios. Of course, prior to all this, the actual mechanism for production of secondary particles in high-energy hadronic collisions should be clearly understood and decisively established. But for low-energy antiprotons as there has been a reversal of direction of discrepancy in the very recent times we shall have to re-examine very carefully and critically the comments we made so far and conclusions we arrived at. Before drastically changing our ideas about this issue, we would like to have these experimental results, meanwhile, checked and confirmed by several groups clearly and separately.

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REFERENCES

[1] S. P. Ahlen, S. Barwick, J. J. Beatty, C. R. Bower, G. Gerbier, R. M. Heinz, D. Lowder, S. McKee, S. Mufson, J. A. Musser, P. B. Price, M. H. Salamon, G. Tarbe, A. Tomasch and B. Zhou: *Phys. Rev. Lett.*, **61**, 145 (1988).

[2] *a)* B. Sadoulet: *Proceedings of the XV SLAC Summer Institute*, SLAC Report No. 328 (August 1987), p. 277; *b)* A. W. Wolfendale: Private communication (July 1988); *c)* S. McKee: private communication (August 1988); *d)* S. W. Barwick: private communication (September 1988).

[3] G. Basini, F. Bongiorno, M. Ricci, P. Spillantini, S. Bartolucci, A. Capone, D. De Pedis, A. Codino, G. Auriemma, E. Lamsanna, S. Petara and A. Sciubba: *Nuovo Cimento A*, **93**, 311 (1986).

[4] A. Buffington, S. M. Schindler and C. R. Pennypacker: *Astrophys. J.*, 248, 1179 (1981).

[5] *a)* R. L. Golden, S. Horgan, B. F. Mauger, G. D. Bhadwar, J. L. Lacy, S. A. Stephens, R. R. Daniel and J. E. Zipse: *Phys. Rev. Lett.*, 43, 1196 (1979); *b)* E. A. Bogomolov, N. D. Lubyanaya, V. A. Ramanov, S. V. Stepanov and M. S. Shulakova: *Proceedings of the XVI ICRC (Kyoto)*, Vol. 1 (1979), p. 330.

[6] *a*) T. K. GAISSER and R. H. MAURER: *Phys. Rev. Lett.*, **30**, 1264 (1973); *b*) G. D. BHADWA R. L. GOLDEN, M. L. BROWN and J. L. LACY: *Astrophys. Space Sci.*, **37**, 283 (197
[7] R. J. PROTHEROE: *Astrophys. J.*, **251**, 387 (1981).
[8] R. J. PROTHEROE: *Astrophys. J.*, **254**, 391 (1982).
[9] W. R. WEBBER: *Proceedings of the XX ICRC*, Vol. **2** (Moscow, 1987), p. 80.
[10] D. MULLER and J. TANG: *Proceedings of the XIX ICRC OG-6.2-6, Lajol California.*
[11] D. MULLER and K. TANG: EFI Preprint No. 86-62 (University of Chicago, Ill., 198
[12] K. MITSUI, Y. MINORIKAWA and H. KOMORI: *Nuovo Cimento C*, **9**, 995 (1986).
[13] Y. MINORIKAWA and K. MITSUI: *Lett. Nuovo Cimento*, **41**, 333 (1984).
[14] F. TAKAGI: *Prog. Theor. Phys.*, **65**, 1350 (1981).
[15] A. S. CAROLL, I. H. CHIANG, T. F. KYCIA, K. K. LI, M. D. MARK, D. C. RAHM, W. BAKER, D. P. EARTY, G. GIACOMELLI, A. M. JONCKHERRE, P. F. M. KOEHLER, P. MAZUR, R. RUBINSTEIN and O. FACKLER: *Phys. Lett.*, **80**, 319 (1979).
[16] S. N. GANGULY and B. V. SREEKANTAN: *J. Phys. A*, **9**, 311 (1976).
[17] YU M. SHABELSKII: *Sov. J. Nucl. Phys.*, **44**, 117 (1986).
[18] A. M. ROSSI, G. VARINI, A. BUSSIERE, E. ALBINI, D. D'ALESSANDRO and G. GIACOME *Nucl. Phys. B*, **84**, 269 (1976).
[19] UA(5) COLLABORATION: *Z. Phys. C*, **33**, 1 (1986).
[20] *a*) J. WDOWCZYK and A. W. WOLFENDALE: *J. Phys. G*, **13**, 411 (1987); *b*) *Proceedings of XX ICRC in Moscow*, Vol. **5**, 157 (1987).
[21] T. CHEUNG and P. K. MACKEOWN: *J. Phys. G*, **13**, 687 (1987).
[22] J. WDOWCZYK and A. W. WOLFENDALE: *J. Phys. G*, **10**, 257 (1984).
[23] J. WDOWCZYK and A. W. WOLFENDALE: *Nuovo Cimento*, **54**, 433 (1979).
[24] S. A. STEPHENS and R. L. GOLDEN: Preprint, TIFR Bombay (India), SP-IR-88 (1988).
[25] F. W. STECKER, R. J. PROTHEROE and D. KAZANAS: *Astrophys. Space Sci.*, **96**, (1983).
[26] *a*) F. W. STECKER and A. W. WOLFENDALE: *Nature*, **309**, 37 (1984); *b*) J. SZABELSKI, WDOWCZYK and A. W. WOLFENDALE: *Nature*, **285**, 386 (1980).
[27] C. J. CESARSKY: *Composition and Origin of Cosmic Rays*, edited by M. M. SHAPIRO (Reidel Publ. House, Dordrecht, 1983), p. 175.
[28] S. A. STEPHENS: *Astrophys. Space Sci.*, **76**, 87 (1981).
[29] S. A. STEPHENS: *Nature*, **289**, 267 (1981).
[30] S. BHATTACHARYYA and PRATIBHA PAL: *Nuovo Cimento C*, **9**, 961 (1986).