

## SECONDARIES IN $P\bar{P}$ COLLIDERS AT SPS ENERGIES AND A MULTIPLE PRODUCTION MODEL

SUBRATA BHATTACHARYYA

*Physical and Earth Science Division, Indian Statistical Institute, Calcutta — 700035, India*

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The recent experimental results obtained from the *CERN  $P\bar{P}$*  colliders at *SPS* ( $\sqrt{S} = 540$  GeV) energies have here been analysed on the basis of a new multiple production model proposed by Bandyopadhyay and Bhattacharyya. It is shown here that the model can describe the data fairly well and passes some crucial tests even at such high energy.

### *1. Introduction*

Physics at the collider energy has in recent times attracted much attention and interest mainly for the two reasons: one, the colliders have really made energy available roughly one order higher in magnitude than the highest *ISR* energy and have thus opened up enormous facilities to study and compare the relative merits and demerits of various many particle production models; two, it satiates to a considerable extent the man's — rather the scientists' — endless cravings for and ceaseless attempts at reaching the higher and still higher energies in the laboratory. Colliders are, therefore, considered to be a landmark of progress in the development of High Energy Physics.

Thanks to the *CERN  $P\bar{P}$*  colliders and Alpgard et al.<sup>1)</sup> there has in recent times been a blizzard of some revealing experimental findings at a super high energy ( $\sqrt{S} = 540$  GeV). The main purpose of this paper is to examine whether the multiparticle production model proposed by *Bandyopadhyay and Bhattacharyya*<sup>2-5)</sup> can account for the cardinal characteristics reported by Alpgard et al. and to draw attention to some major triumphs of this model at the said *SPS* energy ( $\sqrt{S} = 540$  GeV). The latest *UA(5)* experiment by Alpgard et al. noticed an unmistakable rise of the  $K/\pi$  ratio at superhigh energy and this was our prediction long ago. At that time, we had to seek support for it through some phenomena in the cosmic ray physics<sup>6)</sup>. So the near-confirmed detection of the rise of the ratio with energy in the laboratory is surely an indicator of the intrinsic strength of our model.

This multiple production model, based on some radical ideas about the structure of hadrons, reproduced<sup>2-5)</sup> the experimental data quite satisfactorily up to the *ISR* high energy region. Now, what we propose to do here is to check whether the model stands at such high (*SPS*) energies as  $\sqrt{S} = 540$  GeV. Speaking in plain terms, just this is our motivation in the present paper.

The organisation of the paper is as follows: Section 2 presents the summary of the reported experimental results. In Section 3 we have given just the outline of the model of hadrons used here and the vignettes of the multiple production models. The Section 4 deals with the theoretical results and their comparison with the experimental data. The Section 5 is devoted to overall discussion and conclusions.

## 2. Summary of the experimental results

Let us now first point out the key experimental features reported by Alpgard et al.<sup>1)</sup> which we would like to explain here from the standpoint of a new multiple production model: (i) the corrected average charged hadron multiplicity has been measured to be  $\langle n_c \rangle = 28.9 \pm 0.4$  in *P $\bar{P}$*  collider at  $\sqrt{S} = 540$  GeV; (ii) Some violations of the standard form of the *KNO* scaling are observed at  $S = 540$  GeV; (iii) On the basis of some plausible assumptions the measurements record roughly 12% kaons and 9% baryons-antibaryons. These fractions represent an increase from *ISR* energy (e. g., at  $\sqrt{S} = 53$  GeV the ratios were 9% and 5%, respectively). This apart, the production rates of charged and neutral kaons are consistent only with being equal; (iv)  $K/\pi$  ratio rises clearly with energy; (v) The average number of photons per event is  $34 \pm 2$ , about 30% higher than the mean of charged particles which gives  $\eta/\pi^0 \simeq 30\%$ ; (vi) No high multiplicity events having features corresponding to centauro events are found to occur. These apart, there are a few other minor features which we did not address ourselves to.

## 3. Sketches of the hadron model and the multiple production models of the secondaries

According to Bandyopadhyay's ideas<sup>7)</sup>, hadrons participating in purely strong interactions can be seen as arrays of constituent pions and some spectators. The

number of pions and spectators may vary from hadron to hadron. On this basis Bandyopadhyay has succeeded in relating all the quantum numbers with the geometry of the particles. The  $SU(3)$  symmetry of hadrons has also been generated<sup>1)</sup>. The structures of proton and anti-proton, according to this model, are given by  $(\pi^+ \pi^0 \nu_\mu)$  and  $(\pi^- \pi^0 \nu_\mu)$ , respectively. From the viewpoint of this model, strong interactions involving no exchange of hypercharge are caused by the interactions between the points in the incident hadron with pions in the target hadrons. So, according to this model, such hadronic reactions essentially boil down to pion-pion interactions.

In the field of interaction, the pion in the structure of the incident proton releases a  $\rho$  meson and still remains pion. The  $\rho$  meson (Fig. 1) may now decay into  $\omega$  and  $\pi$ ,  $\omega$  in its turn may again break up into  $\rho$  and  $\pi$  and the chain continues unless the final  $\rho$  meson is absorbed by the pion in the target proton. The  $\rho$  and  $\omega$  mesons change positions alternately liberating free pions as two-sided sprays. The pions so produced may belong to any of the three varieties depending on the charge state of the  $\rho$  mesons. Multiplicity of any variety will be assumed to be on the average just one-third of the total average multiplicity.

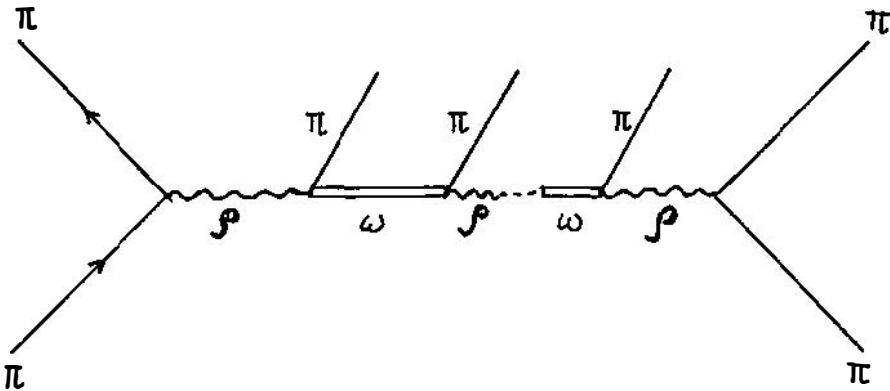


Fig. 1 Multiple production of secondary pions in hadronic collisions according to the present mechanism.

Production of kaons takes place in the following way. The  $\rho$  mesons in Fig. 2 emitted by the interacting core pions in the projectile may break down into  $\Phi^0$  and  $\pi$  mesons. These  $\pi$  mesons may now again give rise to  $\rho$  and  $\Phi^0$  mesons and this  $\rho - \pi$  chain may continue until the final  $\rho$  meson is absorbed by the target proton. The  $\Phi^0$  mesons so liberated may now break up into  $(K^+ K^-)$  or  $(K^0 \bar{K}^0)$  pairs. So there is a likelihood of equal production of  $(K^+ K^-)$  and  $(K^0 \bar{K}^0)$  if and only if the decay widths are nearly same for both the processes from the parent  $\Phi^0$  mesons. But the  $\rho\pi\Phi^0$  coupling constant suffers from a large uncertainty which is roughly one order of magnitude. Both the  $(K^+ K^-)$  or  $(K^0 \bar{K}^0)$  pairs may emerge on both sides of the horizontal  $\rho\pi$  chain.

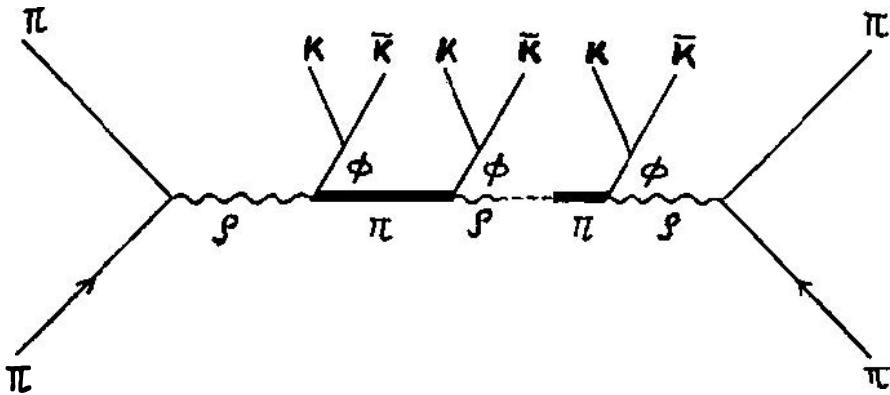


Fig. 2. Multiple productions of  $K \bar{K}$  ( $K^+ K^-$  or  $\bar{K}^0 K^0$ ) secondaries in hadronic collisions from the viewpoint of the present model.

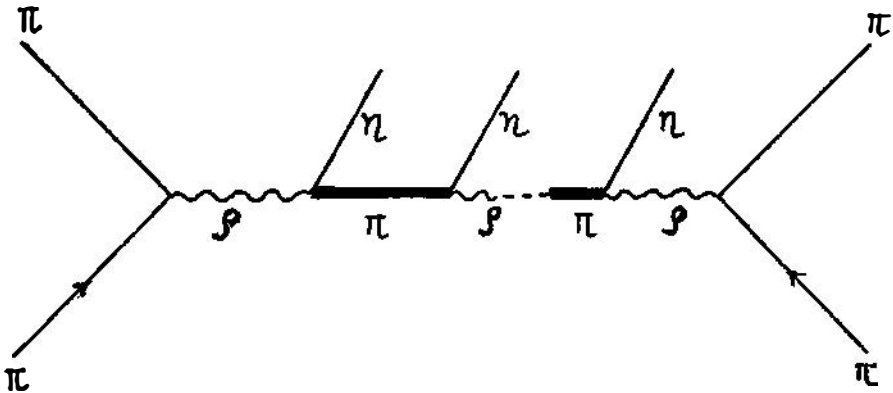


Fig. 3. The proposed mechanism for eta meson production in hadronic collisions.

Production of  $\eta$  mesons occurs in the same way as the pions through  $\rho\eta\pi$  coupling (Fig. 3) instead of  $\rho\omega\pi$  coupling for pions. The alternation now takes place between  $\rho$  and  $\pi$  with emission of free mesons at each vertex. Here too, the  $\eta$  mesons shall come out as sprays alternately on the upward and downward sides of the horizontal chain. There is of course, large uncertainty in the magnitude of the  $\rho\eta\pi$  coupling constant<sup>9)</sup>.

The non-leading secondary baryons, according to this model, are the decay products of the pionic secondaries. This will just be done by introducing a  $B\bar{B}$  vertex<sup>23)</sup> at the end of the secondary pions shown in Fig. 1. This gives a nice clue to understand recently much-talked-about centauro events, if they occur at all.

However, some points need to be stated here emphatically. True, our model does not look like the typical jet models. But it has been shown by us in a recent work<sup>9)</sup> that this model can explain all the salient observational features of the jet models which have so long been considered to be the unmistakable pointers to

jettiness. And the model essentially presents a two-sided spray of hadron secondaries in a sequential chain mechanism and thus conforms to the contention by R. Orava<sup>10)</sup>: »Jets mean different things for different people: a quark combining with quark antiquark pairs in the chromomagnetic field, a tree like parton shower, «a limited transverse momentum spray of hadrons», a shower of hadrons contained in an angular cone, a cluster of hadrons in the momentum space, a consequence of constraints imposed by the transversely limited phase space. For some individuals there are no jets and for some others jets are a quest for a life-long dedicated search«. Quite obviously, ours is a model which portrays jets as «limited transverse momentum sprays of hadrons».

The main features of the multiple production model are presented below: (a) this is a dynamical model with the predominant roles of the vector mesons and with  $t$ -channel openings for hadronic reactions where as for  $e^+ e^- \rightarrow$  hadrons this becomes an  $s$ -channel interactions, (b) the omnipresence<sup>11)</sup> of the leading particle effect ( $LPE$ ) in hadron-hadron collisions has been taken care of just by a single and simple parametrisation which is justifiable as well as verifiable. The absence of the leading particle effect in  $e^+ e^-$  annihilations has also been nicely explained<sup>12)</sup>, (c) the model does not admit of any strict compartmentalisation between the low- $p_T$  and the large- $p_T$  multiple production processes. They are seen as the two-tier behaviour of the same dynamics with only concomitant changes in the kinematics, (d) save and except a single parametrisation, there is no hand-inserted or arbitrary factor in the model, (e) the model predicts a clear breaking of the Feynman scaling at high energies excepting in very small- $p_T$  regions. A recent cosmic ray experiment also vindicates this stand<sup>13)</sup>, (f) it can accommodate the idea of *universality*<sup>14)</sup> of the charged hadron multiplicity in a dynamical, unambiguous and even quantitative way.

#### 4. Theoretical results and comparison with data

We will analyse here data for  $P\bar{P}$  interactions at  $\sqrt{S} = 540$  GeV. But before starting this some points deserve special mention. From the viewpoint of the present model, although the basic interaction in all hadronic reactions is the same  $\pi\pi$  reaction one has to consider the various interactions on a case-to-case basis with regard to only the following two points: (i) total number of diagrams contributing to the particular production process, (ii) conversion of  $S_{\pi\pi}$ , the c. m. energy squared for the interacting  $\pi\pi$  system into the original  $S$ , the c. m. energy squared for the given projectile and target hadrons. Both the  $PP$  and  $P\bar{P}$  reactions stand on the same footing vis-a-vis the above-mentioned twin points.

The only difference between these two processes arises from the possible ( $\pi^+ \pi^-$ ) annihilation reaction exclusively in  $P\bar{P}$  interactions and not in  $PP$  reactions. However, we neglect here this difference and treat them as equivalent which, of course, may not be altogether correct and justified.

So far as the numerical calculations are concerned, it is immaterial whether the secondaries — whatever may be the variety — are produced in the same or opposite sides of the main propagator line as argued in Ref. 9. But the point becomes very important when one considers the actual physical mode of production.

In some previous papers<sup>2-5)</sup> the detailed Feynman diagram calculations of the above type of diagrams have been presented. The relevant results will simply be plucked here for our purpose from those papers. According to the present model, the average multiplicities of pions kaons and baryons in  $P\bar{P}$  and  $PP$  (excepting the small annihilation channel contribution in  $P\bar{P}$  scattering) at high energies shall be

$$\langle n_{\pi^+} \rangle = \langle n_{\pi^-} \rangle = \langle n_{\pi^0} \rangle \simeq .33 S^{1/3} \quad (1)$$

$$\langle n_{K^+} \rangle = \langle n_{K^-} \rangle = \langle n_{K^0} \rangle = \langle n_{\bar{K}^0} \rangle = 1.8 \times 10^{-2} S^{2/5} \quad (2)$$

and

$$\langle n_P \rangle_{non-leading} = \langle n_{\bar{P}} \rangle_{non-leading} = 1.03 \times 10^{-2} S^{2/5}. \quad (3)$$

Here I must add a note on our kaon and baryon multiplicity. We made a minor mistake in one<sup>2b)</sup> of our papers dealing in detail the production of kaons and baryons. In the same paper in one place we took  $K_{max}^2/m_{\pi}^2 \simeq S_{eff}/m_{\pi}^2 \simeq S/GeV^2$  but in another place we assumed  $K_{max}^2 \sim S \epsilon$  with  $\epsilon \ll 1$ . This somewhat anomalous — rather self contradictory — stand was removed by the subsequent uniform parametrisation  $K_{max}^2 \simeq S m_{\pi}^2$  and the changed expressions for average multiplicities of kaons and baryons were reported in Ref. 3.

The expressions given above give a good description of the average multiplicity data of pions, kaons and baryons at the *ISR* region. Straightforward application of these formulae gives the average multiplicity for pions somewhat higher than the experimental value but reproduces the percentage for kaons and baryons quite satisfactorily. The theoretically obtained values of kaons and baryons turn out to be roughly 12% and 10%, respectively. In fact, in a previous publication<sup>5)</sup> we cast doubt on the validity of the standard form of the *KNO* scaling and suggested a new form it — not by altering the scaling parameter,  $z = n/\langle n \rangle$  as suggested by Alpgard et al.<sup>1a)</sup> — but by retaining it and the spirit contained in the proposed *KNO* scaling. From the above expressions, the  $K/\pi$  ratio stands to be

$$K/\pi \simeq 5.4 \times 10^{-2} (\sqrt{S})^{.14}. \quad (4)$$

The solid curve in Fig. 4 depicts our theoretical prediction. Although the order of magnitude as well as the qualitative nature of  $K/\pi$  is in good agreement with data our curve does not agree exactly with the curve one can draw from the experimental points depicted by Alpgard et al. Some physical factors might be at play causing this departure which will be discussed in the next section.

Non-prompt photons are produced mainly through  $\pi^0 \rightarrow 2\gamma$  decay so the process for photon production in  $P\bar{P}$  collides becomes

$$P\bar{P} \rightarrow CX \quad \perp_{1,2} \quad (5)$$

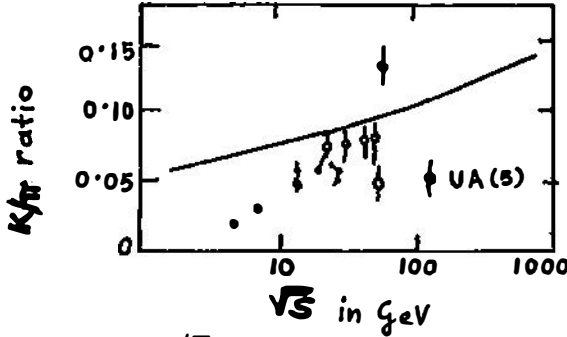


Fig. 4. Plot of the  $K/\pi$  ratio versus  $\sqrt{S}$  (GeV). The solid line is our theoretical plot. Data points are from Ref. 1 b.

the invariant cross section for which can be written as<sup>15)</sup>

$$\sigma = \int \frac{dS_c}{2\pi} \frac{2\sqrt{S_c} \Gamma(C \rightarrow 1,2)}{(S_c - m_c^2)^2 + m_c^2 \Gamma^2} \text{Tr}(\rho \cdot A^*) \sigma_c$$

$$d\mathcal{L}^i p S(S_c, \rho_1, \rho_2) \tag{6}$$

where  $\rho$  and  $A$  are the production and decay density matrix elements for particle  $C$ . For the  $\pi^0 \rightarrow \gamma_1 \gamma_2$  decay,  $\text{Tr}(\rho \cdot A^*)$  is a constant and taking the narrow width limit we can write

$$E_{\gamma_1} \frac{d\sigma}{dp_{\gamma_1}^3} = 8\pi \int \left( E_{\pi^0} \frac{d\sigma}{dp_{\pi^0}^3} \right) \frac{d^3 p_{\pi^0}}{E_{\pi^0}} \frac{d^3 p_2}{4E_2} \frac{\delta^4(p_{\pi^0} - p_1 - p_2)}{(2\pi)^2} =$$

$$= \frac{1}{2\pi} \int E_{\pi^0} \frac{d\sigma}{dp_{\pi^0}^3} \frac{d^3 p_{\pi^0}}{E_{\pi^0} E_2} \delta(E_{\pi^0} - E_1 - E_2). \tag{7}$$

If we neglect the mass of the  $\pi^0$  so that the produced  $\gamma$  rays are collinear with  $\pi^0$ , then, operation of the  $\pi^0$  angular integration yields

$$E_{\gamma} \frac{d\sigma}{dp_{\gamma}^3} = 2 \int_0^1 E_{\pi^0} \frac{d\sigma}{dp_{\pi^0}^3} \frac{d^3 Z}{Z} \tag{8}$$

$$\frac{2 p_{\gamma}}{\sqrt{S}}$$

where

$$Z = \frac{p_{\gamma}}{p_{\pi^0}}$$

Integrating the right hand side with some reasonable approximations it is seen that

$$E_{\gamma} \frac{d\sigma}{dp_{\gamma}^3} \simeq E_{\pi^0} \frac{d\sigma}{dp_{\pi^0}^3}. \tag{9}$$

This is experimentally justified by the same

$$F(x) = \int \frac{2E}{\pi \sqrt{S}} \frac{d\sigma}{dp_T^2 dx} dp_T^2$$

for  $\gamma$  rays and that for  $\pi^0$  from 250 GeV/c  $\pi^-P$  interactions at least for small  $x$  values.

Now ascribing the parenthood of non-prompt photons to neutral pions we get the average number of non-prompt photons at  $\sqrt{S} = 540$  GeV

$$\langle n_\gamma \rangle \cong 23.5. \quad (10)$$

The average multiplicity of photons has been derived here on the basis of the  $S^{1/3}$  dependence which clearly shows a more rapid energy dependence of  $\langle n_\gamma \rangle$  than  $\log S$  as seen and indicated by N. Arata<sup>16</sup>). But the experimental value is  $34 \pm 2$  which is roughly 30% higher than the mean of charged particles. The origin of this excess of photons is ascribed to the  $\eta$  mesons. In Fig. 3 we have shown the model for  $\eta$  meson production. So this provides an opportunity to investigate our model for  $\eta$  meson production. The expression for average multiplicity of  $\eta$  mesons, according to our model, is obtained in the same manner as that for pions. The expression may be put as (of course neglecting the annihilation channel contribution)

$$\langle N_\eta \rangle = 9 \left( \frac{f_{\eta\pi}^2 K_{max}^2}{64 \pi^2} \right)^{1/3}. \quad (11)$$

As we have used the earlier parametrisation  $K_{max}^2/m_\pi^2 \simeq S_{eff}/m_\pi^2 \simeq S/\text{GeV}^2$  here we will use  $K_{max}^2 \simeq S m_\pi^2$ . The  $\rho\eta\pi$  coupling constant is given by the ratio  $Y$ ,

$$Y = \frac{(g_{\rho\eta\pi}^2/4\pi)}{(g_{\rho\pi\pi}^2/4\pi)} \simeq .03 \text{ to } .008.$$

But the know that

$$(g_{\rho\pi\pi}^2/4\pi) \simeq 2.5.$$

Now if we use the  $\rho\eta\pi$  coupling value with  $Y = .03$ , we get

$$\eta/\pi^0 \simeq 60\% \quad (12)$$

which is in agreement with Banner et al<sup>17</sup>). Obviously if the lower limit is taken the value falls to the measured  $\eta/\pi^0 \simeq 25\%$ . Although unless the uncertainty in the value of the coupling constant is removed the exact percentage of the ratio  $\eta/\pi^0$  cannot be ascertained, we may at least hope to give a fair account of the data from what has already been possible despite the limitations and the constraints.

### 5. Discussion and conclusions

It was really very challenging to us to check whether the model proposed by us (P. B. and S. B.) can reproduce the experimental data at such energies as  $\sqrt{S} = 540$  GeV. From the agreements arrived at between the experimental findings and our theoretical results it will possibly not be an overstatement to comment that there is sufficient reason to be satisfied — although no room for complacency. Over a wide range of energies from the *ISR* region to the *SPS* level the model works well with usual approximations and somewhat tolerable assumptions. We do not have any control over the uncertainties in the values of coupling constants which are serious impediments to the correct determination of the parameters and proper assessment of the model. Only time can remove these hindrances.

I did not present here the theoretical plot for pion multiplicity and kaon multiplicity separately as experimental values at various energies in this superhigh energy domain are still not available. The author wonders here how Alpgard et al. can state in a conclusive vein that the  $UA(5)$

experiment excludes stronger forms of energy dependence (than  $\ln^2 S$ ) such as  $S^{1/4}$  in consonance with some others<sup>18)</sup> values of energy ( $\sim \sqrt{S} = 540$  GeV) in such a superhigh energy region and in the intermediate energies between  $\sqrt{S} = 63$  GeV to  $\sqrt{S} = 540$  GeV. Vis-a-vis the nature of the energy dependence of the average charged hadron multiplicity, the only substantial claim they can make is that the  $\ln^2 S$  nature of the average multiplicity proposed by the  $QCD$  and some other models can accommodate the data with their chosen values for the coefficient terms. But one cannot be certain about whether the parametrisations made at  $\sqrt{S} = 53$  to  $63$  GeV will remain valid even at such a ultrahigh energy as  $\sqrt{S} = 540$  GeV. This apart, the role of the leading particle effect has not yet been studied in this extremely high energy region. These two factors viz. the parametrisation and the leading particle effect might have had a disturbing role in our model calculations too. But, surely, this is no more than an educated guess.

Now follow some comments about the centauro events. The  $UA(5)$  experiment has negated their observation at  $\sqrt{S} = 540$  GeV. But these events have been reportedly found in some cosmic ray experiments at higher energies. It would be wise at the present stage to keep the issue open from the viewpoint of any theoretical model until further specific data either in support of the events or against them are to hand. As in the case of pions, there is a chance for some excess production of baryons too over this wide energy band as the average multiplicity of baryons follow  $S^{2/5}$  dependence according to our model. So if the events do really exist and are finally established the model under discussion might be able to justify them. Otherwise it will be our task to find out the sources of error in our deductions arriving at such unobserved excesses, if any.

Further surprises seem to lie ahead with the start of the Fermilab  $P\bar{P}$  collider project<sup>19)</sup> which is now being readied for operation. The first spurt of results is expected circa 1984. With the increased energy of the tevatron, 1000 GeV vs. 270 GeV at the *CERN SPS*, the Fermilab  $P\bar{P}$  project portends some exciting results and all the model-builders in High Energy Physics should keep their fingers crossed.

Summing up finally and somewhat reiterating we can state that the present model — with all its pros and cons — seems to be in a comfortable position in so far as its capacity to explain the observed features at the *CERN  $P\bar{P}$*  collider results is concerned. This is very heartening especially in the background of the null results<sup>20-22)</sup> in the quark-searches conducted in the cosmic ray experiments and in the latest high energy accelerators as the basic model of hadrons utilised here rests on a quarkless universe.

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## PRODUKTI U $P\bar{P}$ SUDARIMA NA SPS ENERGIJAMA I MODEL VIŠEČESTIČNE PRODUKCIJE

SUBRATA BHATTACHARYYA

*Physical and Earth Science Division, Indian Statistical Institute, Calcutta-700035, India*

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Analizirani su novi eksperimentalni rezultati dobiveni na CERN-ovim  $P\bar{P}$  sudarima pri SPS ( $\sqrt{s} = 540$  GeV) energijama u okviru novog modela Bandyopadhyaya i Bhattacharyye za višečestičnu produkciju. Pokazano je da model opisuje podatke prilično dobro te da zadovoljava neke bitne testove na visokim energijama.