IL NUOVO CIMENTO VOL. 20 C, N. 4 Luglio-Agosto 1997

Antibaryon yields in ultrahigh-energy collisions and the astroparticle implications (*)

S. BHATTACHARYYA, D. ROY and R. BHOWMICK

Theoretical Physics Research Group, Physics and Applied Mathematics Unit (PAMU)
Indian Statistical Institute - Calcutta 700035, India

(ricevuto il 27 Giugno 1996; approvato il 28 Novembre 1996)

Summary. — Some of the most recent results on antibaryon production in some ultrahigh-energy nuclear collisions are being analysed on the basis of a particle production model which has had some intrinsic features of non-standard nature. It is seen that the model could accommodate the data without any induction of the quark-gluon plasma (QGP) ideas which have, truly speaking, become a fad in the domain of the ultrahigh-energy nuclear collisions with some probable implications for or impact upon astroparticle physics.

PACS 96.40 – Cosmic rays.

1. – Introduction

Studies on baryon-antibaryon production in high-energy heavy nuclear collisions provide, it is believed, strong clues to unravel the mysteries still unsolved on the particle production scenario in general, and particle structure in particular. According to the ideas based on quark-gluon frames, the ratio $\overline{\Lambda}/\overline{P}$ supplies information on the production of strange antiquarks compared to light antiquark. Irrespective of the ideas held on the structure of particles, it is undoubtedly true that "antibaryon yields in central nucleus-nucleus collisions are expected to exhibit the subtle interplay between various partonic and/or hadronic production and annihilation processes as well as properties of a possible partonic equilibrium of the system" [1]. Furthermore, the results would also throw light on the nature and dynamics of high-energy nuclear collisions. Besides, the interests in antibaryon production spring from the predictions of the quark-gluon plasma (QGP) ideas on the excess production of strange baryon-antibaryons in the ultrahigh-energy collisions. Finally, the controversy [2-4] on the asymmetry in baryon-antibaryon productions in the universe is still a very hot topic and a really unsettled question in the domain of astroparticle interface physics. In fact,

---

(*) The authors of this paper have agreed to not receive the proofs for correction.

these last two issues provided the prime and necessary stimulus to take up this problem as the subject for all investigations of the past, though the present study is not concerned in a straightforward manner with the latter question.

2. – Experimental results: The relevant points

The symmetry of the experimental results *vis a vis* the strange-particle scenario in high-energy hadron-hadron, hadron-nucleus and nucleus-nucleus collisions could be presented as follows: i) The ratio of the production of kaon to pion (K/π) increases very, very slowly with c.m. energy. ii) Compared to lambda-bar ($\overline{\Lambda}$) production, production of lambdas (Λ) is clearly higher by roughly one order of magnitude. iii) The lambda/pion ratios present no clear energy dependence but the measurements of the ratios depict a mass number dependence of both the projectile and the target. iv) Rise of the inclusive cross-section for productions of strange particles with increasing c.m. energy is observed. v) The ratio of lambda particles to antiprotons shows a queer dependence on the target nucleus. Though on the basis of one or two experiments, no definite statement could be made but the ratios seem to show a fall-off with heavier nuclear targets.

In the previous work we addressed some of the prospects of heavy nucleus-nucleus collisions and the present study pertains, in the main, to the behaviour of the strange to non-strange antibaryons.

3. – The model for strange hyperons-antihyperons: The physical picture

According to the present model, all high-energy interactions are basically the pion-pion interactions. The interacting pions in the structure of a proton (projectile) release a ϱ-meson which then decays into ω and π mesons; ω in its turn may again break up into ϱ and π and the chain continues until the final ϱ-meson is absorbed by any of the constituent pions of the target proton. The mechanism gives rise to pions which may belong to any of the three varieties depending on the charge state of the parent ϱ or ω mesons. Multiplicity of any variety will be assumed to be on the average just one-third of the total average multiplicity. On the basis of the similar arguments, cross-sections are normally expressed by the average of the positive and negative π-mesons.

We proposed that the secondary pions produced by the collisions of the projectile and the target nucleons (free or those inside the nucleus) may become the source of all strange or non-strange baryon production. The following steps would give the scheme for the production of the strange baryons from the secondary pions which are reduced in turn just to the virtual states. The following are the proposed modes [5] for the probable production of some strange baryons:

$$\pi^+ \rightarrow \Lambda^0 \overline{\Sigma}^- \quad \text{or} \quad \overline{\Lambda}^0 \Sigma^+ ,$$

$$\pi^- \rightarrow \Lambda^0 \overline{\Sigma}^+ \quad \text{or} \quad \overline{\Lambda}^0 \Sigma^- ,$$

$$\pi^0 \rightarrow \Lambda^0 \overline{\Sigma}^0 \quad \text{or} \quad \overline{\Lambda}^0 \Sigma^0 .$$

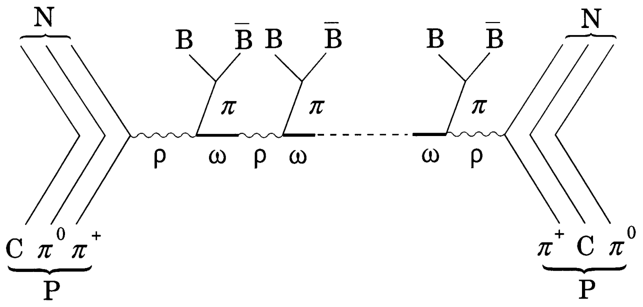

Fig. 1. – Proposed diagram for production of strange baryon-antibaryon pairs in PP (NN) collisions according to the present mechanism of particle production.

For other particles the model proposes

$$\pi^0 \rightarrow \Lambda\Xi^0,$$

$$\pi^+ \rightarrow n\Sigma^+,$$

$$\pi^- \rightarrow \Lambda\Xi^- / \Xi^0\Omega^- / n\Sigma^- .$$

Σ^0 and $\bar{\Sigma}^0$ will have a very very small production rate as they have very a short mean life (10^{-4} s) and they decay mainly into $\Lambda\gamma$ or $\bar{\Lambda}\gamma$. The diagram attached hereto (fig. 1) presents the proposed mechanism for the production of both antiprotons and other strange antibaryons in a generalized form.

4. – Model-based estimation

The calculations would proceed according to the Feynman diagram techniques followed on the basis of the diagram given in fig. 1. Though we would not present here the details of the calculations (as it would be repetitive) we would simply pick up some relevant relations from our previous papers and make use of them. But, before doing it, we need to present here some very basic expressions [6] relating the concrete parameters which entered into the present calculations.

4·1. *Basic relations.* – The differential rapidity cross-section $d\sigma/dy$ is given by

$$\frac{d\sigma}{dy} = \int E \frac{d^3\sigma}{dp^3} d^2p_T \tag{1}$$

and the average multiplicity of particle is given by

$$\langle n \rangle = \frac{\Sigma n\sigma_n}{\sigma_{\text{incl}}} = \frac{1}{\sigma}\int_0^{y_{\max}} dy \frac{d\sigma}{dy} = \int_0^{y_{\max}} dy \frac{dn}{dy}, \tag{2}$$

where

$$\frac{dn}{dy} = \frac{1}{\sigma_{\text{incl}}}\frac{d\sigma}{dy} \tag{3}$$

and

$$\sigma_{\text{tot}} = \langle n \rangle \sigma_{\text{incl}}, \tag{4}$$

with

$$\langle n\rangle^2 \sigma_{t_{\text{incl}}} = \int \sigma^2_{\text{incl}} \frac{\mathrm{d}^3 p}{E} \,. \tag{5}$$

4'2. *Model-based derivations of the working formulae.* – The expression for the average multiplicity of any variety of strange antibaryon is given by

$$\langle n_{\bar{\mathrm{B}}\mathrm{s}}\rangle = \frac{9}{16\pi}\left[\frac{4 f^2_{\varrho\omega\pi} G^2_{\pi\Sigma\Lambda}}{625}\right]^{1/5} S^{\varepsilon}, \tag{6}$$

with

$$\frac{f^2_{\varrho\omega\pi}}{4\pi} = \frac{16}{\text{GeV}^2} \quad \text{and} \quad \varepsilon \leqslant 0.20\,, \quad \frac{G^2_{\pi\Sigma\Lambda}}{4\pi} = 11^{(10)} \quad \text{and} \quad \langle n_{\bar{\mathrm{P}}}\rangle = 2\times 10^{-2} S^{1/4}. \tag{7}$$

Again, the inclusive cross-sections for the antiproton and antihyperon are given by the generalized expressions [7-9]

$$\left(E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3}\right)_{\mathrm{PP}\to\bar{\mathrm{P}}\mathrm{x}} \simeq C_{\bar{\mathrm{P}}} \exp\left[\frac{0.66}{\langle n_{\bar{\mathrm{P}}}\rangle^{3/2}} \cdot \frac{(p_{\mathrm{T}})^2_{\bar{\mathrm{P}}} + \mu^2_{\bar{\mathrm{P}}}}{1-x}\right] \exp\left[-25.4\langle n_{\bar{\mathrm{P}}}\rangle\, x\right], \tag{8}$$

$$\left(E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3}\right)_{\mathrm{PP}\to\bar{\Lambda}\mathrm{x}} = C_{\bar{\Lambda}} \exp\left[\frac{0.0016}{\langle n_{\bar{\Lambda}}\rangle^{4/5}} \cdot \frac{(p_{\mathrm{T}})^2_{\bar{\Lambda}} + \mu^2_{\bar{\mathrm{P}}}}{1-x}\right] \exp\left[0.0082\right] x\,. \tag{9}$$

Values of $C_{\bar{\mathrm{P}}}$ and $C_{\bar{\Lambda}}$ are obtained from our previous work and used here for calculation. For nucleus-nucleus collisions the results

$$\langle N\rangle_{A_i A_t} = 1.1[\alpha_c]_{A_i A_t}\langle n_{\text{sec}}\rangle_{\mathrm{PP}}[0.75R + 1.5][\langle\nu\rangle^{2/3} + 1]\,, \tag{10}$$

with

$$\langle\nu\rangle \simeq \frac{1}{2}\left(A_i^{1/3} + A_t^{2/3}\right);$$

α_c values are to be obtained from some of our previous work and $\langle n_{\text{sec}}\rangle_{\mathrm{PP}}$ is the production of the relevant secondary particle.

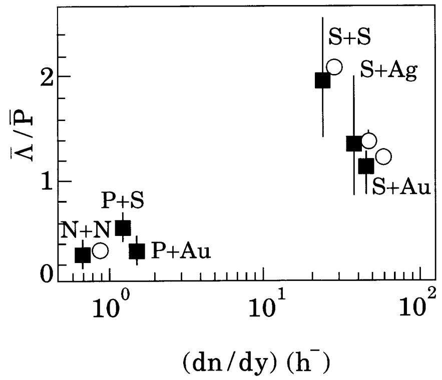

Fig. 2. – Comparison of the production ratio of antihyperon to antiproton in the various nucleon-nucleon, nucleon-nucleus and nucleus-nucleus collisions. The plot shows the ratio of antihyperon to antiproton yield *vs.* the values of $(\mathrm{d}n/\mathrm{d}y)(\mathrm{h}^-)$. The open circles depict the present model-based estimates.

TABLE I. – *Comparison of some relevant observables between the experimental measurements and the model-based calculations for various types of reactions.*

Reaction	$\frac{dn}{dy}(\bar{P})$		$\frac{dn}{dy}(\bar{\Lambda})$		$\bar{\Lambda}/\bar{P}$		$\frac{dn}{dy}(h^-)$	
	Experimental	Calculated (SCM) (Present work)	Experimental	Calculated (SCM) (Present work)	Experimental	Calculated (SCM) (Present work)	Experimental	Calculated (SCM) (Present work)
N + N	$(2.0\pm0.2)\times10^{-2}$	1.5×10^{-2}	$(0.5\pm0.2)\times10^{-2}$	0.42×10^{-2}	0.25 ± 0.10	0.28	0.75 ± 0.04	0.85
P + S	$(3.2\pm0.3)\times10^{-2}$	—	$(1.5\pm0.3)\times10^{-2}$ $(2.05\pm0.25)\times10^{-2}$	—	0.5 ± 0.1	—	1.3 ± 0.2	—
P + Au	$(4.6\pm0.5)\times10^{-2}$	—	$(1.5\pm0.5)\times10^{-2}$	—	0.3 ± 0.1	—	1.6 ± 0.1	—
S + S	0.4 ± 0.1	0.33	0.75 ± 0.16	0.65	$1.9^{+0.7}_{-0.6}$	1.97	25 ± 1	27.5
S + Ag	0.6 ± 0.2	0.55	0.75 ± 0.19	0.72	$1.3^{+0.7}_{-0.5}$	1.31	40 ± 2	45.8
S + Au	0.7 ± 0.2	0.68	0.75 ± 0.10	0.82	$1.1^{+0.4}_{-0.3}$	1.21	47 ± 5	52.2

TABLE II. – *Comparison of the experimental average multiplicity ratio of* $\bar{\Lambda}/\bar{P}$ *with the present* SCM-*based calculaions for various interactions.*

Reaction	Experimental multiplicity ratio $\bar{\Lambda}/\bar{P}$	Model (SCM)-based calculated results on the basis of multiplicity ratio (Present work) $\bar{\Lambda}/\bar{P}$
P + P	0.25 ± 0.10	0.23
S + S	$1.9^{+0.7}_{-0.6}$	1.28
S + Ag	$1.3^{+0.7}_{-0.3}$	1.41
S + Au	$1.1^{+0.4}_{-0.3}$	1.55

TABLE III. – *Comparison of the various models and the experimental measurements* (*The* SCM-*based results are presented in this table by averaging the values of the ratios obtained from table I and table II*.

Reaction	Experimental $\bar{\Lambda}/\bar{P}$	Model-based calculated results		
		General thermal approach $\bar{\Lambda}/\bar{P}$	ROMD $\bar{\Lambda}/\bar{P}$	SCM (Present work) $\bar{\Lambda}/\bar{P}$
P + P	0.25 ± 0.10	0.2	0.3	0.255
S + S	$1.9^{+0.7}_{-0.6}$	1.1	1.5	1.625
S + Ag	$1.3^{+0.7}_{-0.3}$	0.9	—	1.36
S + Au	$1.1^{+0.4}_{-0.3}$	0.9	1.1	1.38

The calculated results are depicted in table I, table II and table III and some ratios are shown in fig. 2.

The expressions (10) had to be adjusted for the "*A*" dependence of the strange and non-strange antibaryons in a somewhat phenomenological way and the values of the used coupling constants were obtained from Vasylev *et al.* [10].

5. – Concluding remarks

The model we applied here for the production of particles in high-energy hadron-hadron collisions (the SCM model) and also the one of nucleus-nucleus collisions reproduce the observed data with a modest degree of success, although the latter suffers from strong phenomenological traits, of course, with some well-grounded reasonings.

Quite obviously, the models which were made use of did not introduce any tint of the quark-gluon plasma hypothesis and obtained some values for the ratios for the non-strange to strange variety of antibaryons which are in fair accord with the experimental measurements. This provides in essence modest support to some of the authors [11-13] who showed commonly a non-QGP view on the same issue, albeit from different angles. However, this study does not throw any light on this question of baryon-antibaryon asymmetry as such, but the question of strange antibaryon production has had a strong astroparticle implication via the proposed quark-gluon plasma (QGP) hypothesis which is being discarded here outright. The latest report on production of the antihydrogen ($\overline{\mathrm{H}}$) beyond any pale of doubt by Baur *et al.* [14] has made the choice of our problem really very exciting and challenging for even future researches [15] in this direction.

REFERENCES

[1] NA 35 COLLABORATION (ALBERT T. A. *et al.*), *Phys. Lett. B*, **366** (1996) 56.
[2] BRAUN-MUNZINGER P., STACHEL J., WESSELS J. P. and XU N., *Phys. Lett. B*, **365** (1996) 1.
[3] BHATTACHARYYA S. and CHAKRABORTY S., to be published in *Nuovo Cimento C*.
[4] *a*) PANCHAPAKESAM N., *Astrophysics and Cosmology*, edited by SINHA B. and MOITRA R. K. (Narosa Publishing House, New Delhi) 1995, p. 71. *b*) MALLICK S., *Astrophysics and Cosmology*, edited by SINHA B. and MOITRA R. K. (Narosa Publishing House, New Delhi) 1995, p. 82.
[5] BHATTACHARYYA S., CHAKRABORTY S., ROY D. and BHOWMICK R., to be published in *Hadronic J. Suppl.* (1996).
[6] KAIDALOV A. B. and TER MARTIROSYAN K. A., *Sov. J. Nucl. Phys.*, **39** (1985) 979.
[7] BHATTACHARYYA S., *J. Phys. G.*, **14** (1988) 9.
[8] BHATTACHARYYA S. and PAL P., *Nuovo Cimento C*, **9** (1986) 961.
[9] BHATTACHARYYA S., *Hadronic J.*, **11** (1988) 183.
[10] VASYLEV A. M., GINZBURG I. F. and PERLOVSKII L. I., *Sov. J. Nucl. Phys.*, **25** (1977) 573.
[11] NA 36 COLLABORATION (ANDERSON E. *et al.*), *Phys. Lett. B*, **327** (1994) 433.
[12] CAPELLA A., *Phys. Lett. B*, **364** (1995) 175.
[13] UA(1) COLLABORATION (BOCQUET G. *et al.*), *Phys. Lett. B*, **366** (1996) 441.
[14] BAUR G. *et al.*, *Phys. Lett. B*, **368** (1996) 251.
[15] EADES J., *Nature*, **379** (1996) 674.