

ON THE ROLE OF BARYON EXCITATION IN VERY HIGH-ENERGY COLLISIONS

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At all energies above a few GeV, the probability that two nucleons emerge from a collision in one of the excited baryon states (with or without change of strangeness number) seems to be much higher than the probability that one or both emerge in a nucleon ground state.

As a result, the secondary particles fall naturally into two categories:

(i) The particles created in the collision centre (pionization process); their energy remains constant in the centre-of-mass system but their number increases in proportion to the energy available for particle creation. Therefore, in the laboratory system, both their energy and their number increase approximately proportional to the square root of the primary energy.

(ii) Pions created at some distance from the collision centre by decay of excited baryons (or hyperons); their number remains constant but the laboratory energy of those emitted by the incident baryon increases approximately linearly with the primary energy.

Within the accuracy of available experimental data, all the parameters characterizing the two processes seem to be independent of primary energy between $\gtrsim 9$ GeV and $\lesssim 10^4$ GeV.

The discovery of isobaric states of the nucleon and hyperon system suggests an investigation of the role which such states play in nuclear interactions at extremely high energies.

It has been shown recently ^{1, 2)} that in $p-p$ collisions at 2 GeV and at 2.85 GeV, one- and two-pion production is dominated by the excitation and the subsequent decay of one or both of the colliding nucleons. The

observations are in fairly good agreement with the model developed by Sternheimer and Lindenbaum ³⁾.

In the more complicated collisions which occur at 25 to 30 GeV it is less easy to assess the role of excited baryon states. Conceivably, mesons from isobar decay could be as numerous at this energy as mesons produced more directly, i.e. in what has been called the pionization process. The two different mechanisms of meson production are not easily distinguished experimentally since the momentum ranges in which they contribute overlap strongly.

But at much higher energies, between 10^3 and 10^6 GeV, the problem of distinguishing between the two production mechanisms becomes comparatively simple again. Although in this energy region decay mesons are now responsible for only a very small fraction of the created particles, most of them appear in a momentum interval entirely different from that of particles produced in the pionization process. The decay meson (or mesons) of the baryon which is emitted forward in the centre-of-mass system carries in almost all cases a very large fraction of the primary energy and is thereby distinguished from the bulk of other created particles. The corresponding decay meson of the baryon emitted backward assumes a similar role when transformed to the mirror system (in which incident and target nucleons are interchanged).

INELASTICITY IN HIGH-ENERGY INTERACTIONS

This distinguished position occupied by decay mesons from isobaric states is a consequence of the considerable degree of elasticity which characterizes high-energy interactions.

It is a well-established property of high-energy nuclear collisions that normally only a minor fraction of the available energy is expended in the creation of new particles, while most of it is retained by the incident nucleon. The evidence for this high degree of elasticity comes mainly from studying the development of the nuclear cascade in the atmosphere; when a cosmic-ray primary of great energy impinges from outside, nucleons become the principal carriers of the cosmic-ray energy into the lower part of the atmosphere and constitute the backbone of the extensive air shower which develops. All but the most energetic of the observed large electron showers would die out within a few radiation lengths if they were not rejuvenated whenever the nucleon or nucleons constituting the shower core collide and transfer some of their energy to neutral pions. In order to account for the energy spectrum of nucleons at various depths in the atmosphere, it is necessary to assume that nucleons transport a substantial fraction of the available energy from one collision point to the next. The mean value of this fraction η is related to the interaction and absorption mean free path of the nuclear component in the atmosphere by the relation

$$\frac{\lambda_{\text{int}}}{A_{\text{abs}}} = 1 - \eta^\gamma,$$

where γ is the exponent of the primary energy spectrum.

According to the detailed analysis of Baradei *et al.*⁴⁾, the absorption mean free path varies somewhat with energy and has the value

$$\begin{aligned} A &= 148 \text{ g/cm}^2 \text{ at } E \approx 10^{12} \text{ eV,} \\ &135 \text{ g/cm}^2 \text{ at } E \approx 10^{13} \text{ eV, and} \\ &129 \text{ g/cm}^2 \text{ at } E \approx 5 \times 10^{13} \text{ eV.} \end{aligned}$$

Using $\lambda_{\text{int}} = 75 \text{ g/cm}^2$ and $\gamma = 1.5, 1.8$ and 2 , respectively, as the most likely exponents of the primary nucleon spectrum in the appropriate energy region, one finds that the elasticity parameter η lies in the rather narrow interval $0.60 \leq \eta \leq 0.65$ (*).

THE LARGE TRANSFER OF ENERGY TO SINGLE DECAY MESONS

Because of the high degree of elasticity in nucleon-nucleon collisions, the effect of isobar production on the energy distribution of created particles is extremely marked. This is illustrated in Table I where it has been assumed, for the sake of simplicity, that all excited non-strange baryons decay to the ground state by the emission of a single pion, and that excited strange baryons decay in two steps, by prompt emission of a single pion followed by delayed pion emission. The occurrence of somewhat more complicated decay schemes does not invalidate the line of argument. The table shows that if baryons emanating with high energy from a collision were distributed among the known (non-strange or strange) states roughly in proportion to their respective statistical weights, then on the average more than 25% of the primary energy (i.e. considerably more than half of the energy spent in creating new particles) would be given to the decay pion, while a comparatively small amount of energy remains to be shared between the very large number of pions and kaons produced in the pionization process (which in collisions of 10^3 to 10^4 GeV is responsible for the creation of between 20 and 30 particles).

It is also evident from Table I that there exists a plausible, and not necessarily rare, mechanism by which it is possible to transfer a very large fraction (up to $\sim 70\%$) of the primary energy to a single pion without transmitting a large transverse momentum, a phenomenon which has been observed occasionally^{6, 7)}.

Thus, the excitation of colliding baryons, if it occurs frequently, must have a profound effect on the subsequent behaviour of secondaries produced in high-energy nucleon-nucleon interactions and must play a decisive role in all phenomena associated with the nuclear cascade and the development of air showers in the atmosphere.

The question remains as to how frequent is the process of baryon excitation in high-energy collisions

(*) The elasticity parameter has also been obtained less directly by using the barometric coefficient and the zenith angle distribution of air showers of given size; by this method, values of η as low as 0.50 have been obtained⁵⁾. An inconsistency between these experimental data and those of Ref.⁴⁾ cannot be excluded. But it must be remembered that the low value for η is derived not only for a somewhat higher energy range but also from more complex events characterized by a constant total energy rather than by a constant energy per nucleon; the interpretation of the observations, therefore, requires specific and not necessarily justified assumptions regarding the composition of the primary radiation before they can be related to properties of nuclear interactions.

TABLE I
 Decay of relativistic baryons by single pion emission
 (* indicates delayed emission)

| M (MeV) | I | J | W (Statistical weight) | $\langle \epsilon_\pi/E_B \rangle_{\text{avge}}$ % | $(\epsilon_\pi/E_B)_{\text{max}}$ % |
|----------------|-------|---------|-----------------------------|---|--|
| $S = 0$ | | | | | |
| 938 | $1/2$ | $1/2$ | 4 | — | — |
| 1238 | $3/2$ | $3/2$ | 16 | 21 | 39.5 |
| 1510 | $1/2$ | $3/2$ | 8 | 31 | 60.3 |
| 1680 | $1/2$ | $5/2$ | 12 | 34 | 67.7 |
| . | . | . | . | . | . |
| . | . | . | . | . | . |
| . | . | . | ≥ 40 | $\geq 25\%$ | . |
| $S = -1$ | | | | | |
| Λ 1115 | 0 | $1/2$ | 2 | 14.5* | 22.9* |
| Σ 1192 | 1 | $1/2$ | 6 | 19* | 34.5* |
| Y_1^* 1385 | 1 | $> 3/2$ | ≥ 12 | 18.9+11.7* | 35 +14.9* |
| Y_0^* 1405 | 0 | ? | ≥ 2 | 19.2+11.7* | 35.5+14.8* |
| 1520 | 0 | $> 3/2$ | ≥ 4 | 23.6+10.8* | 45.2+12.5* |
| 1815 | 0 | $> 3/2$ | ≥ 4 | 30.7+10.1* | 60.6+ 9.1* |
| . | . | . | . | . | . |
| . | . | . | . | . | . |
| . | . | . | ≥ 30 | $\geq 25\%$ | . |
| $S = -2$ | | | | | |
| Ξ 1314 | $1/2$ | $1/2?$ | ≥ 4 | 13.7*+10.1* | 23* +11.2* |

and also what role do strange baryons play in the process. Anticipating the remainder of this paper, the answer to the first question appears to be that excitation of baryons is very frequent and that cases in which the baryons emerge in the nuclear ground state are comparatively rare. The second question, however, cannot yet be answered with any degree of confidence, although plausible arguments can be given to indicate that strange and non-strange baryons emerge from high-energy interactions with comparable frequency.

EXPERIMENTAL EVIDENCE FOR THE EXTREMELY NON-UNIFORM DISTRIBUTION OF ENERGY AMONG CREATED PARTICLES

Observations to the effect that a single pion often carries the major part of the energy liberated in a high-energy interaction have been reported and commented on by many authors⁶⁻¹⁰. It has repeatedly

been emphasized that such phenomena can be interpreted as de-excitation of baryon states by meson emission¹¹⁻¹³). However, evidence that such phenomena dominate at high energy cannot easily be derived from isolated observations. It can be deduced, for instance, from data given by Perkins⁵) who states that per gram of air near the top of the atmosphere the rate of production of pions above ~ 500 GeV constitutes 7% of the rate of occurrence of nuclear interactions above 500 GeV. Since in this energy region the power law describing the nucleon spectrum has an index between 1.5 and 1.8, the production of mesons with energies above 500 GeV is as frequent as the number of nuclear collisions with energies of 2000 or 3000 GeV. When combined with the high degree of elasticity which characterizes such collisions, the statement implies that on the average one pion carries away 15 to 25% of the available energy.

A second observation⁵) which qualitatively leads to a similar conclusion is that near the top of the

atmosphere the number of interactions per gram of emulsion in which more than 1000 GeV is liberated in the form of γ rays is nearly as large as the number of γ rays with more than 1000 GeV produced per gram of air in the residual atmosphere above the emulsion. This observation again indicates that, often, most of the energy which goes into the γ -ray component is given to one or perhaps two neutral pions.

A third illustration of the fact that the fractional energy given to π^0 mesons in high-energy interactions is preferentially either very low or very high but not smoothly distributed between these extremes, is provided by the work of Babayan *et al.*¹⁴⁾ The authors measured the energy given to π^0 mesons by a single strongly interacting particle falling on a thick carbon absorber. In the upper layer of the absorber, i.e. in the first interaction, energy transfers of $\sim 10\%$ or of 80% to the leptonic component were shown to be relatively frequent, while intermediate values were significantly rarer.

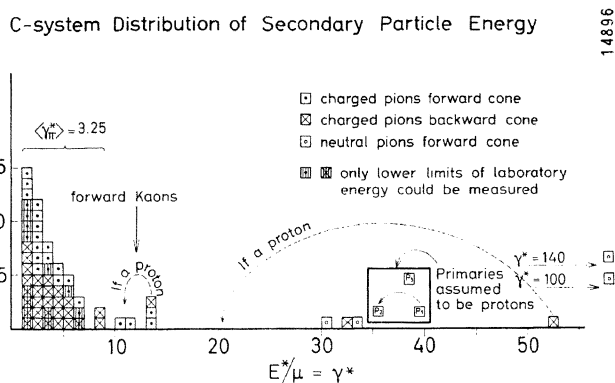


Fig. 1

A good example of the commonness of this extremely unequal energy distribution among created particles is illustrated also in Fig. 1. The histogram is based on measurements by Jain^{15, 16)} carried out on three jets of comparable energies (2500-4000 GeV), all of them characterized by a small number of grey and black tracks. The chance of discovering such jets depends on their peculiarities and is strongly biased in favour of cases in which a π^0 meson is emitted

with very large energy; a similar event in which a charged meson carries a large fraction of the primary energy would often escape detection. However, the bias is reversed if one transforms to the mirror system; a charged meson, which in the laboratory system is very slow and often easily identifiable, becomes the main carrier of energy while the corresponding slow neutral pion develops only a small electron shower and escapes detection. Thus, one must expect that in the C-system neutral pions from baryon decay belonging to the forward cone and charged pions belonging to the backward cone should appear well separated in energy from the bulk of the shower particles.

This feature is clearly visible in the figure. The fact that in three collisions, at least five created particles are found which seem to be well separated from all others in momentum space, supports the assumption that the excitation of colliding baryons is a frequent process at 3000 GeV, as it is at 2 GeV.

THE ENERGY OF MESONS CREATED IN THE PIONIZATION PROCESS

The histogram of Fig. 1 shows also that the energy with which most of the created particles are emitted in the C-system is quite low:

$$\langle \gamma_{\pi^0}^* \rangle = 3.25 \quad \text{or} \quad \langle p_{\pi^0}^* \rangle = 430 \text{ MeV/c. } (*)$$

This is in good agreement with the value observed by Dobrotin *et al.*¹⁷⁾ at 300 GeV, but it is not in agreement with the mean centre-of-mass momenta of negative pions in 24 GeV $p-p$ collisions. Here the British group¹⁸⁾ reports

580 MeV/c for 2-pion events, and

520 MeV/c for 4-pion events.

Since it is not reasonable to assume that at 3000 GeV pions are produced in the C-system with less energy than at 24 GeV, one is led to the conclusion that the pions observed at the accelerator are probably a mixture of mesons from isobar decay and mesons from the pionization process. The observation also implies

(*) According to the fireball model, the bulk of mesons are evaporated (i.e. emitted isotropically with low energy) from a number of centres (most frequently two) which are not completely at rest in the C-system. The mean momentum with which mesons are emitted from such centres must then be less than the 430 MeV/c measured in the C-system, but it cannot be less than the observed transverse momentum ($\langle p_{\perp} \rangle \approx 250-350$ MeV/c) and therefore the velocity of the fireballs must be comparatively small. According to the Cracow group¹⁹⁾, this velocity is just adequate to account for the anisotropy in the angular distribution of the created particles as observed in the C-system.

that the mean energy in the pionization spectrum remains quite small and must be essentially independent of primary energy. If one then assumes it to be equal at 24 GeV and at 3000 GeV, one finds that at the PS or AGS machine essentially all pions which have more than 8 GeV in the laboratory system ought to be due to isobar decay. The number of such energetic pions observed at CERN and Brookhaven corresponds, in fact, to the assumption that excited baryons play a large role, and that nucleons emerging in the ground state are rather infrequent. This is the result of an analysis which has been carried out recently by Yash Pal (private communication).

ENERGY INDEPENDENT PROPERTIES OF NUCLEON-NUCLEON COLLISIONS

In view of the prominent role which excited baryon states appear to play both at very low and very high energy, it seems worth while tentatively to consider the hypothesis that nuclear collisions from a few GeV up to energies of at least a few times 10^4 GeV can be described by a model characterized by the same small set of parameters.

The following assumptions seem adequate for the purpose:

(1) Baryons emerging from a collision can find themselves in any of the available states with a probability commensurate with their respective statistical weights.

This assumption seems not unreasonable if one considers that, because of the large amount of available energy and the large number of other particles created in the process, all known conservation laws can be satisfied easily.

One consequence of the assumption is that the nucleon ground state occurs in less than 10% of all collisions, irrespective of whether the number of available baryon states is equal to or larger than the number of such states which are known at present (see Table I). A second consequence then is that above ~ 1000 GeV, in at least 90% of all collisions, one (and sometimes two) meson emerges which carries the bulk of the energy given to created particles.

(2) The second assumption concerns the pionization process. In the pionization process, the following features appear to be, on an average, independent of primary energy:

- (a) the fraction of the available energy spent in creating particles;
- (b) the relative number of particles of different types;
- (c) the energy spectrum of the created particles in the C-system or in other systems (F) which are nearly at rest with respect to the C-system ($\gamma_F \ll \gamma_c$).

Assumptions (1) and (2a) together ensure that the inelasticity parameter remains essentially independent of primary energy.

Condition (2b) ensures that at high energies the ratio of γ rays to shower particles approaches a constant value in accord with observations. If condition (2b) is interpreted as holding separately for kaons and for antikaons, then it also determines the mean strangeness value of the emitted baryons and therefore the frequency of hyperon production.

Conditions (2a), (2b) and (2c) taken together determine the energy dependence of multiplicity for all types of created particles.

This simple set of postulates seems to be consistent and at any rate not in conflict with existing data on nucleon-nucleon collisions in the entire range from a few GeV to at least 10 000 GeV. However, it goes beyond established facts and permits predictions (for instance, about the role of isobars at 25-30 GeV) which, while not yet established, are accessible to experimental verification. In particular, the hypothesis implies that pions produced by the large CERN and Brookhaven accelerators with energies above ~ 8 GeV are due almost entirely to isobar decay (and those above 16 GeV to the decay of an isobar whose mass is as large or larger than that of the $^{1/2}, ^{5/2}$ resonance).

The essential element in this mode of description of high-energy interactions, the element which permits one to describe collisions over such a large range of energies by the same parameters, is the division of particle creation into two distinct processes which depend in different ways on primary energy:

- (i) The creation of two isobars which decay at a large distance from the collision centre (50-100 Fermi for collisions in the range 10^3 to 10^4 GeV). In the laboratory—or in the mirror system—one of them gives rise to one (or two) meson whose energy increases *linearly* with that of the primary particle.

(ii) The pionization process which gives rise to a number of different types of particles (in fixed proportions) whose laboratory energy increases approximately *as the square root* of the energy.

While it is not to be expected that such a simple set of assumptions is strictly true, it does seem to be approximately valid. One can therefore use the hypothesis to make precise predictions to be compared with better experimental data which will become available in the future. Deviations represent then real physical changes in the nature of high-energy interactions (as distinct from trivial kinematical effects); though apparently small, such changes are bound to occur as the available energy of colliding particles becomes very large compared to their rest mass.

NUMERICAL VALUES OF PARAMETERS CHARACTERIZING THE PROCESS OF PARTICLE CREATION

We now chose a set of parameters which are independent of collision energy and seem to represent correctly existing experimental data from below 9 GeV to at least 10 000 GeV:

(1) The two baryons emerging from a high-energy collision have, on the average, a mass $M_B = 1.4M_p$. This is equal to a mass composed of the nucleon ground state and of the states N_1^* and N_2^* averaged according to their appropriate statistical weights. (Very nearly the same value is obtained if the strange baryon states Λ , Σ , Ξ , Y_1^* and Y_0^* are included in the averaging process.) Since the mean fractional energy retained by a baryon which decays to the nucleon ground state by single pion emission is given by

$$\frac{M_B^2 + M_p^2 - \mu_\pi^2}{2M_B^2},$$

each of the baryons will, on the average, transfer 25% of its energy to one and sometimes two decay mesons.

(2) In decaying to the ground state, these two baryons together will emit about 2.5 pions. (We neglect the possibility that a K meson may be emitted occasionally.)

(3) The number of particles created in the pionization process is proportional to the energy available in the C-system of the collision and is given by

$$n' = 0.54(\gamma_c - 1). \quad (*)$$

Of this number, $5/6$ are pions and $1/6$ are kaons. (This division is dictated by the observed ratio of γ rays to shower particles in jets.)

Assuming charge symmetry, the number of charged particles emitted from a $p-n$ collision is given, therefore, by

$$n_{\text{ch}} = 0.64n' + 1 + \frac{2}{3} \times 2.5 = 0.64n' + 2.67.$$

For $p-p$ collisions, n_{ch} should be higher by about 0.5. The calculated and observed multiplicities are compared in Table II.

The ratio between the number of γ rays and of charged particles emitted is given by

$$\frac{n_\gamma}{n_{\text{ch}}} = \frac{2}{3} \frac{(\frac{5}{6}n' + 2.5)}{n_{\text{ch}}},$$

provided one assumes that all γ rays originate in π^0 decay.

The ratio of charged kaons and antikaons to charged pions is given by

$$\left(\frac{K + \bar{K}}{n_\pi} \right)_{\text{ch}} = \frac{1}{2} \left(\frac{K^+}{\pi^+} + \frac{K^-}{\pi^-} \right) = \frac{1}{8} \frac{n'}{(\frac{5}{6}n' + 2.5)}.$$

These values are also listed in Table II.

(4) The mean energy in the C-system of pions produced in the pionization reaction is taken to be

$$\left\langle \frac{\epsilon_\pi^*}{\mu_\pi} \right\rangle = \langle \gamma_\pi^* \rangle = 3.25,$$

in agreement with the data presented in Fig. 1.

(5) For kaons, the mean C-energy is not known. But if one assumes that kaons are emitted isotropically from the same centres (fireballs) as pions, the fact that they have roughly the same mean transverse momentum as the pions suggests that $\langle \gamma_k^* \rangle < \langle \gamma_\pi^* \rangle$. Provisionally, we shall take $\langle \gamma_k^* \rangle = 1.8$.

If one neglects the energy transferred to created baryon-antibaryon pairs, which cannot yet be estimated

(*) Because this formula applies only to the pionization part of meson creation, it differs in its energy dependence from the frequently quoted $n \sim E^{1/4}$ law. The two relations give similar results for the total number of created particles up to collision energies of $\sim 10^4$ GeV. Neither law seems to apply above $\sim 10,000$ GeV.

TABLE II

Calculated multiplicities in high-energy $p-n$ collisions
(Experimental data are put in brackets)

| E_0 (GeV) | n' (particles created in pionization process) | n_{ch} (charged particles emitted) | n_γ/n_{ch} | $\left(\frac{K+\bar{K}}{\pi}\right)_{\text{charged}}$ | $n_Y+n_{Y^*}$ ^(b) |
|-------------|--|--|-----------------------------------|---|------------------------------|
| 9 | 0.7 | 3.1 {3.06±0.14 (p-n)} ²¹⁾ {3.42±0.10 (p-n)} | 0.66 | 0.03 | 0.04 |
| 25 | 1.47 | 3.6 ^(a) {4.2±0.1 (p-p)} ¹⁸⁾ | 0.69 | 0.05 | 0.08 |
| 1000 | 11.9 | 10.3 {9.9±1.4} ²²⁾ | 0.81 {0.82±0.05} ⁵⁾ | 0.12 | 0.66 |
| 3000 | 21.0 | 16.1 {16} ^{5, 16)} | 0.83 | 0.13 | 1.18 |

(a) For $p-p$ collisions the predicted value is $n_{ch} \approx 4.1$.

(b) On the assumption that in production $(K+Y)/(K+\bar{K}) = 1$.

from existing data, the elasticity of nucleon-nucleon collisions is determined by the chosen parameters and given by

$$\eta = \left[1 - \frac{n' \left(\frac{5}{6} \mu_\pi \langle \gamma_\pi^* \rangle + \frac{1}{6} \mu_k \langle \gamma_k^* \rangle \right)}{2M_p \gamma_c} \right] \left(\frac{M_B^2 + M_p^2 - \mu_\pi^2}{2M_B^2} \right) = 0.65.$$

This is in good agreement with the value derived previously from the ratio of interaction and absorption mean free paths of nucleons in the atmosphere. Also, the value appears to be consistent with the elasticity measured at 24 GeV. (For protons on carbon nuclei, Pal *et al.*²⁰⁾ obtain $\eta = 0.57 \pm 0.07$; for $p-p$ collisions it would be expected to be slightly larger.)

The mean energy given to the particles which are created in the pionization process represents 15% of the total available energy (of which the pions get slightly more than two-thirds). Another ~20% of the primary energy are liberated at a large distance from the collision centre and, in most cases, are given to one decay pion.

HYPERON PRODUCTION

At 25 GeV, about half of all kaons are produced together with an antikaon and the other half together with a hyperon. If this branching ratio is independent of collision energy, one can calculate on the basis of the formulae given above the mean strangeness of the emitted baryons

$$\langle S \rangle = -0.015(\gamma_c - 1). \quad (*)$$

If valid, this would imply that one half of the baryons which emanate from collisions at 3000 GeV have strangeness $S = -1$ or -2 . At this energy, therefore, the baryons appear as strange or non-strange particles with a frequency roughly corresponding to the number of known available states of each type.

At 25 GeV, the formula predicts that 8% of all $p-n$ collisions lead to the production of a hyperon; it could be somewhat smaller for $p-p$ collisions and is therefore not necessarily in disagreement with observations.

(*) The validity of this formula is restricted to the region in which the multiplicity of created particles is proportional to the energy available in the C-system ($E \leq 10^4$ GeV).

SOME CONCLUSIONS REGARDING COSMIC RADIATION IN THE ATMOSPHERE

There is as yet no evidence on whether or not the branching ratio in the production of kaons which one finds at 25 GeV represents already an asymptotic high-energy value; therefore, the question of how many very high-energy hyperons occur in the cosmic radiation cannot yet be decided.

It should, however, be pointed out that, even if the probability of changing the strangeness of the leading baryon in a single collision is as low as 5-10%, a near-equilibrium between nucleons and hyperons will be established rather quickly in a condensed medium, i.e. whenever successive collisions take place too rapidly to permit hyperon decay between the points of interaction. Thereby, the branching ratio in kaon production at high energies becomes accessible to experimental observation. (Allowance will have to be made for the fact that emission of some very high-energy hyperons can take place also in other strangeness conserving processes, for example the decay $N_2^* \rightarrow K + A$.)

Another conclusion which can be drawn from the extremely unequal energy distribution among pions, associated with the prominent role of excited isobars, is that in the cosmic radiation nearly all pions, γ rays, or muons with energies above a few hundred GeV come from baryon decay; they are then descendants of parents whose energy is higher by a factor of the order of four. Those originating in pionization reactions need parents whose energy is higher by at least a factor fifty; they are very much rarer, because of the steepness of the primary energy spectrum.

* * *

In conclusion, it should be emphasized that while the division of the particle creation process into the mechanism of pionization and of baryon decay probably corresponds closely to the actual situation, the assumed complete energy independence of all the collision parameters may well turn out to be an oversimplification, in spite of the fact that it seems to account quite well for those features of high-energy collisions which are more or less firmly established at present.

LIST OF REFERENCES

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DISCUSSION

WILLIAMS: There is one point which seems not quite to fit in, that is the value of the elasticity inferred from the nucleon cascade in the atmosphere. The assumed collision mean free path seems too short. If you assume 75 g/cm² as the collision mean free path, then it is easy to find out that this implies for the nucleon-nucleon collision cross-section something between 50 and 60 mb, which seems very high. I would expect that the right collision mean free path is probably something like 100 g/cm², corresponding to a nucleon-nucleon collision cross-section of about 25 to 30 mb.

PETERS: I agree that the precise value of the inelasticity is still open to some question, and therefore also the average mass of the emitted baryon. The last data which I have seen, and which were reported at Kyoto, are the basis of the values which I have presented. Maybe they are correct, because they were obtained rather directly from measurements on high-energy nucleons; they do not involve showers or anything like that.

LINDENBAUM: I think that 30 mb may be a little low because you are talking about nucleon-nucleon cross-sections. The last measured values are more like 38-40 and they are constant from a few GeV up to 25 GeV, so it may be that 40 is a better number unless you have a specific reason.

WILLIAMS: Would be not excluded the diffraction scattering which tends to be about one-quarter of that, though?

LINDENBAUM: Not necessarily, because at the highest energies the diffraction scattering may decrease and also, when you are dealing with a many-nucleon nucleus, I am not sure that some of the elastic scattering does not contribute to what one technically defines as the interaction mean free path.

OPPENHEIMER: If this were a Plenary Session, others would say this: that there are some reasons to expect a cross-section to grow. They are not certain reasons, and this has to do with the increasing size and transparency of the nucleons with energy. And therefore, due to the fact that there is no shielding at all, one gets an A and not A^{2/3} law. It would be very nice to know if this is true. There are at this Conference many people who would be delighted for it to be true.

YAMAGUCHI: Dr. Oppenheimer has made an extremely interesting point. However, we are dealing here with pretty low energy compared with that where A times the nucleon-nucleon cross-section is equal to the nucleon-nucleus cross-section. In this respect, cosmic-ray particles are still at low energies.

OPPENHEIMER: I said that this was an effect that was starting gradually, how gradually I do not know. It would not be visible at CERN but would be visible in the higher energy domain.

WEISSKOPF: It is certainly an extremely strange thing which we observe here, namely that you find that only a certain limited number of excited baryons, or isobars, play a role. We do not understand this. Maybe the lifetime comes in; if the lifetime is shorter than a certain amount, then they just are not excited. It is much more natural to assume that there is a continuous transition from the isobars that run along, to those fireballs that stay where they are. You find an interval in between. This is an experimental fact, I suppose, but it is certainly extremely strange and it is not easy to understand.

PETERS: First, let me say something about the lifetime. The lifetime of the ones which are now known is such that at 3000 GeV they decay about 100 F away, i.e. very far from the collision centre. In other words, if there were other lifetimes shorter by factors of 10, they would still show up. Secondly, if one applies a new selection rule and says that certain isobars are strongly favoured over others (i.e. there are very heavy ones, but they do not occur very often), then there is nothing one can say about this from an experimental point of view. But if one wants to say that the mean mass of emitted isobars increases with energy because of the statistical weight of heavier and heavier isobars, then the answer is that it is not so, because then we run into an average inelasticity which is not observed. In fact, the mean mass cannot be higher than two proton masses, even if we produce only a single isobar or, if one prefers, a single fireball, and forget about any pionization process. I think that the limit to the weight of the baryon states which are produced with any reasonable frequency is a real limit obtained from the experiment.

PERKINS: I just wanted to point out that you get this limit on the baryon mass simply by equating everything to the average behaviour. In fact, this inelasticity that you have used, if the exponent γ of the primary spectrum is about 2, is a mean square inelasticity, not a mean value. Only we know in any case that the inelasticity distribution is a very broad one.

FARLEY: I think it might be interesting to discuss your assumption that the baryons come out with a statistical distribution. The question is, how do the baryons have time in this very high-energy and short-time collision to come to a statistical equilibrium? I think there is some evidence that this is not so, for instance in the π^- -proton bubble chamber experiments at CERN, I think it turned out there that the proton kept very much its identity. The frequency of emerging as a proton was much greater than the probability of the proton emerging as a neutron. So there is some tendency for the baryons to keep their identity, and probably you have a rather limited choice of possible isobars. Probably the distribution is not statistical and maybe the spins are not equally populated, and so on.

PETERS: The averaging according to statistical weights is simply a rational way of getting a distribution which roughly gives the right average value. The choice could be justified by the argument that in a collision in which many particles are produced one would have to think up new rules which say that this particular isobar may not be produced, in spite of the fact that one can conserve all those quantities which we know need to be conserved. That may of course be the case. I do not think that the question of time for establishing an equilibrium is involved here, because we are not putting the isobars into equilibrium in each particular case. We only say that the frequency of producing an isobar is roughly proportional to the number of states which exist.

LINDENBAUM: I do not think that the statistical assumption of Peters is unjustified, because he still has this pionization cloud which has essentially been torn away near rest in the centre-of-mass (and this has many pions and kaons) and is a mechanism for allowing a statistical equalization between the two baryon isobars or centres.

AMATI: I would like to say that perhaps there can be some theoretical reasons why the lower mass isobars are very much favoured, as compared to all the higher mass isobars. This would perhaps explain in some way the results of Professor Peters.

MIESOWICZ: I would like to remind you that we observe a number of cases for which, analysing them by means of the fireball model, we get a very high Lorentz factor, $\bar{\gamma}$, for these fireballs

in the c.m. system. So, we cannot in these cases distinguish the fireball mechanism from the excited nucleon model; either we have a very fast fireball in the c.m. system, or we have a very large excitation.

PETERS: The cases I have seen show that when there is a large Lorentz factor, the number of particles is about three. That is what one would expect on the isobar model.

HERZ: I remember a paper by Amati and others where there were a number of vertices in collisions. Now, I am wondering whether it would be possible that in a nucleon-nucleon collision you have one vertex which is the fastest forward, with an outgoing baryon, and then a succession of vertices all of which are essentially pionization vertices, giving you a series of fireballs of all sorts of velocities. I think that a lot of jets are not really consistent with two fireballs but they could well be consistent with quite a number of them, and they would still give a very fast forward baryon.

AMATI: I agree completely with that remark. From the dynamics of multiple production which I presented yesterday, we would expect that the incident nucleon shall carry away a fixed amount of the total energy, and that many of the times it could be converted into an isobar. Besides, we would expect that probably more and more fireballs would come out at higher and higher energies. How fast these fireballs develop is not very clear; we would think that at energies of several hundreds of GeV more than two fireballs would be necessary. I believe that a paper will be presented afterwards by Hayakawa in which there is already some indication in this sense.
