CERN-TH.4649/87

LONGITUDINAL $\bar{\Lambda}$ -POLARIZATION, Ξ ABUNDANCE AND QUARK GLUON PLASMA FORMATION

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A B S T R A C T

The relatively large abundance of Ξ expected to be a peculiar feature for the quark-gluon plasma formed in relativistic nuclear collisions can be readily observed by measuring the longitudinal polarization of $\bar{\Lambda}$ into which Ξ cascades. This characteristic Ξ -signature of the quark-gluon plasma is discussed.

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In hot and dense regions of nuclear matter there should be a high density of strange particles, leading, inter alia, to an abundant formation of multi-strange baryons and antibaryons. This should be the case when the quark-gluon plasma phase expected for hot hadronic matter is formed. It has been argued¹⁾ that the relative abundance of multi-strange antibaryons would then provide a key information about the formation of a quark-gluon plasma. In particular, recent detailed calculations²⁾ suggest that the abundance of anticascades $\bar{\Xi}(\bar{s}\bar{s}q)$ is enriched to about half the abundance of antihyperons $\bar{Y}(\bar{s}\bar{q}q)$. This prediction may be compared to the $\bar{\Xi}/\bar{Y}$ ratio seen in standard hadronic reactions, which, at $\sqrt{s} = 63$ GeV is only 0.06 ± 0.02 in the central rapidity region³⁾. Thus the quark-gluon plasma state would yield a ratio up to ten times greater. This ratio would be a rather characteristic feature of this new state of matter and it is very desirable to measure its value in central nuclear collisions as function of rapidity (and transverse momentum). The parallel ratio $\bar{Y}/\bar{N}$ is 0.27 ± 0.02 when measured in the same experiment at ISR³⁾, while detailed quark-gluon plasma calculations²⁾ predict $\bar{Y}/\bar{N}|_{\text{plasma}} \sim 1 \pm 0.2$. We thus see that the $\bar{\Xi}/\bar{Y}$ ratio is even a more specific observable than the $\bar{Y}/\bar{N}$ ratio. We argue that it provides a simple signature and the more so since the ISR ratios are certainly upper limits for those at $\sqrt{s} = 20$ GeV, relevant to the oxygen run at CERN⁴⁾. However, the $\bar{\Xi}/\bar{Y}$ ratio seems more difficult to establish experimentally. We show in this paper how the measurement of the longitudinal $\bar{\Lambda}$ polarization should easily allow one to establish the ratio of $\bar{\Xi}/\bar{Y}$ abundances. We also give prescriptions for its measurement as well as predictions concerning the magnitude of the expected effect. We assume that the detector permits the observation and measurement of the charged decay "V"s of the neutral $\bar{\Lambda}$ particles. The decaying $\bar{\Lambda}$ particles originate in part in the (rapid) electromagnetic decays of the $\bar{\Sigma}^0$ particles as well as from the weak decays of $\bar{\Xi}^0$, $\bar{\Xi}^-$. All anticascades ultimately become $\bar{\Lambda}$, while only half of all antihyperons $\bar{Y}$ will be in the $\bar{\Lambda}$ -decay chain, of which 64.2% are giving the typical "V" decay pattern. Assuming full acceptance for the "visual" detector for all "V"s, the total sample of all seen "V"-events is

$$N_V = 0.642 \bar{Y} \left(\frac{1}{2} + \bar{\Xi}/\bar{Y} \right) \quad (1)$$

and, should the abundance ratio $\bar{\Xi}/\bar{Y} \sim 1/2$, we see that half of the observed "V"s would be associated with the primordial $\bar{\Xi}$ abundance.

The central point of this paper is the profound difference in the polarization of the $\bar{\Lambda}$ descending from the weak $\bar{\Xi}$ decays. The weak decay polarizes the $\bar{\Lambda}$ -spin longitudinally, the mean value of its helicity being given by the

decay asymmetry parameter α_{Ξ} . In the subsequent weak $\bar{\Lambda}$ decay this polarization is analyzed yielding observable effects. In order to optimize statistics the simplest approach is to consider the so-called up-down asymmetry of the $\bar{\Lambda}$ decay with reference to the plane normal to the $\bar{\Lambda}$ -momentum, i.e., to measure how often in the $\bar{\Lambda}$ rest frame the antiproton appears "above" as compared to "below", with respect to a plane normal to the direction of $\bar{\Lambda}$ -momentum. As will be shown below, this asymmetry is given by

$$\frac{N_u - N_d}{N_u + N_d} = \frac{1}{2} \alpha_{\bar{\Lambda}} P_{\bar{\Lambda}} , \quad (2a)$$

where $P_{\bar{\Lambda}}$ is the $\bar{\Lambda}$ polarization and $\alpha_{\bar{\Lambda}}$ the $\bar{\Lambda}$ decay parameter. Instead of the up-down asymmetry one may consider the expectation value of the cosine of the angle between the antiproton momentum and the direction of the $\bar{\Lambda}$, perhaps less ambiguous experimentally. The factor 1/2 in (2a) is then replaced by a factor 1/3.

We have from the data tables

$$\alpha_{\Lambda} = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013 \quad (2b)$$

and (see below)

$$P_{\bar{\Lambda}} = \alpha_{\Xi} = -\alpha_{\Xi} = \begin{cases} 0.413 \pm 0.022 & \text{for } \Xi^0 \\ 0.455 \pm 0.015 & \text{for } \Xi^- \end{cases} \quad (2c)$$

Hence the total up-down asymmetry of all "V" events is

$$\frac{N_u - N_d}{N_u + N_d} = \frac{N_{\Xi}}{N_{\bar{V}}} \frac{1}{2} \alpha_{\Lambda} \alpha_{\Xi} , \quad (3a)$$

where we have included the relative abundance of all polarized $\bar{\Lambda}$ to the total abundance of "V":

$$\frac{N_{\Xi}}{N_{\bar{V}}} = \frac{\bar{\Xi}}{\frac{1}{2}\bar{Y} + \bar{\Xi}} = \frac{2 \bar{\Xi}/\bar{Y}}{1 + 2 \bar{\Xi}/\bar{Y}} . \quad (3b)$$

With $\bar{\Xi}/\bar{Y}$ in the range 1/2 (resp. 1/3) we expect a negative up-down asymmetry of 14% (resp. 11%). For the "normal" value $\bar{\Xi}/\bar{Y} \sim 0.06$ (at $\sqrt{s} = 63$ and which is certainly less at $\sqrt{s} = 20$ GeV!) we would have an asymmetry of only 1.6%. Naturally, the same analytical form, Eq.(3), is valid with reference to the

baryon abundances with effects being expected to be of similar magnitude, but less characteristic, i.e., less specific to the formation of a quark-gluon plasma.

At this point, one may stress that the longitudinal polarization considered here is of entirely different origin and nature than the transverse polarization of $\bar{\Lambda}$ associated with hadronic formation processes of the particles and which is often discussed in the literature⁵⁾. The transverse polarization also previously briefly explored as signature of quark-gluon plasma⁶⁾ is indeed associated with the up-down asymmetry, with respect to a scattering plane, i.e., containing the incoming projectile momentum and the emerging $\bar{\Lambda}$ momentum. This plane is normal to the plane used for determining the longitudinal up-down asymmetry and therefore there is no mixture between the two measurements as imposed by parity conservation in direct $\bar{\Lambda}$ formation. While rescattering may change the longitudinal polarization, the $\bar{E}/\bar{Y}$ ratio is defined after the time of formation, when the particles have long escaped the dense plasma or hadronic state. It is therefore highly unlikely that the $\bar{\Lambda}$ would scatter before it decays. From parity invariance the transverse and longitudinal polarizations discussed here are orthogonal and multiple scattering in the hadronic gas cannot create longitudinally polarized $\bar{\Lambda}$ out of primordial transverse polarization. Longitudinal polarization of $\bar{\Lambda}$ is thus a unique and practically indestructible signal of the $\bar{E}$ abundance. We further note that $\bar{Q}$ weak decays have a negligible influence over the particle abundances and, in particular, their polarizations, since $\bar{Q}, Q$ are at least five times less abundant than $\bar{E}, E$ ²⁾ and their decay asymmetry parameter ("polarizer" capability) is 5-20 times weaker (depending on the decay channel). The fact that some $\bar{Y}, \bar{E}$ are descendants of strong decays of $\bar{Y}(1385), \bar{E}(1530)$, etc. is also of no consequence, as abundances of these particles are always considered part of $\bar{Y}$ resp. $\bar{E}$ abundance.

The actual measurement of up-down asymmetry is easily possible, as the sample of the "V" events may be constrained only to those in which the baryon-pion identification is unique and their momenta well determined. Boosting the antiproton momentum to the $\bar{\Lambda}$ rest frame and considering the vector product between $\bar{\Lambda}$ -momentum and $\bar{p}$ -momentum we easily establish an up-down criterion:

$$S := \vec{P}_{\bar{\Lambda}} \cdot \vec{P}_{\bar{p}} / P_{\bar{\Lambda}}^2 - E_{\bar{p}} / E_{\bar{\Lambda}} = \begin{cases} \text{positive for up} \\ \text{negative for down} \end{cases} \quad (4)$$

Here we have, as usual, $\vec{p}_{\bar{\Lambda}} = \vec{p}_p + \vec{p}_\pi$ for the respective particle momenta and similarly for their energies $E_i = \sqrt{m_i^2 + p_i^2}$.

We now turn to the more theoretical part of our paper and discuss in turn:

- a) the origin of the relatively large $\bar{E}/\bar{\Lambda}$ abundance ratio;
- b) the polarizing $\bar{E}$ -decay and the analyzing property of the $\bar{\Lambda}$ -decay.

a) Strange antibaryons from a quark-gluon plasma

It is widely expected that in the quark-gluon plasma state the gluon density will be appreciable and nearly that of perturbative QCD statistical quantum description. As a consequence in the numerous G-G collisions, strange quarks (s - $\bar{s}$) are produced as pairs, eventually saturating the phase space cells⁷⁾ even in the short period of the plasma lifetime ($\Omega \sim 6 \cdot 10^{-23}$ sec). This corresponds to an s and $\bar{s}$ -quark density of $0.5/\text{fm}^3$ ($T = 250$ MeV, $m_s = 170$ MeV, $\alpha_s = 0.6$). Model calculations⁸⁾ show that this high strangeness abundance is completely preserved in the following expansion/cooling of the plasma state, since the strange quarks decouple from their equilibrium state with the gluons. Assuming an initial plasma radius of, say, 3 fm, the number of strange quarks available in the hadronisation of the nuclear collision exceeds 100 both for s and $\bar{s}$ quarks. The stated $\bar{s}$ density may then exceed the light $\bar{q}$ density, which is regulated by its chemical equilibrium with the (finite) baryon density of light quarks. The finite value of the baryochemical potential μ_b suppresses through the factor $e^{\mu_b/3T}$ the $\bar{q}$ abundance. Clearly when $\mu_b/3 \gg m_s \sim T$ we obtain even at equilibrium an anomalous state in which $\bar{s}$ -quarks are the dominant antimatter component¹⁾.

In order to establish the ratio of abundances of $\bar{E}$ to $\bar{\Lambda}$ we consider the probabilities P_i of finding the constituent particle in a unit volume V . Incorporating gluons which have to fragment into $q\bar{q}$ -pairs (85%) and $s\bar{s}$ -pairs (15%, $f = 0.15$) we have

$$\frac{\bar{E}}{\bar{\Lambda}} = \frac{(P_s + f P_G)^2 (P_{\bar{q}} + (1-f) P_G)}{B (P_s + f P_G) (P_{\bar{q}} + (1-f) P_G)^2} \quad (5a)$$

Here B is the branching ratio reflecting the possibility that an $s\bar{s}G$ system may make not only the desired system $\bar{s}q\bar{q} + qq$, but also systems such as $\bar{s}q + \bar{q}G$ etc.

Clearly $B < 1$. We have from Eq. (5)

$$B \frac{\bar{E}}{\bar{Y}} = \left(\frac{P}{1-f} + \frac{1}{1-f} P_{\bar{s}}/P_G \right) / \left(1 + \frac{1}{1-f} P_{\bar{q}}/P_G \right) . \quad (5b)$$

In a baryon-rich quark-gluon plasma the last factor in Eq. (5b) is negligible. Using the statistical weights for $P_{\bar{s}}/P_G = 3/8$ we obtain $\bar{E}/\bar{Y} > 0.62$. Including the $\bar{q}$ -density is easy, as $P_{\bar{q}}/P_G = e^{-\mu_b/3T} 6/8$, with the last factor again being statistical. In detailed calculations in which various branchings for the different reactions have been allowed²⁾ the approximate form (5b) is well recovered, and one has

$$\frac{\bar{E}}{\bar{Y}} \approx \frac{3}{4} \frac{1}{1 + 0.8 e^{-\mu_b/3T}} . \quad (6)$$

The sister-ratio of $\bar{Y}/\bar{N}$ is rather model-dependent, since $\bar{q}$ -gluon clusters find many more open channels and this may influence the final result in a more profound manner. Thus the $\bar{E}/\bar{Y}$ ratio is, as shown here, not only easy to measure, but also intrinsically much less model-dependent. It is indeed controlled mainly by statistical weight functions.

b) The polarizing $\bar{E}$ decay and the analyzing $\bar{\Lambda}$ decay

What follows may have appeared familiar to a track-chamber physicist of the early sixties but is probably less familiar to a quark-plasma physicist of the late eighties.

Parity violation in the decay of the $\bar{E}$ and $\bar{\Lambda}$ particles allows in each case a mixture of S and P waves in the final state. This results in a decay asymmetry⁹⁾. As is well known, the angular distribution of the decay nucleon from a completely polarized hyperon at rest is given by:

$$\frac{dI}{d\Omega} = \frac{1}{4\pi} (1 + \alpha \cos \theta) , \quad (7)$$

where θ is the angle between the baryon momentum and the polarization axis (the z axis) and α is the asymmetry parameter.

If the hyperon is only partially polarized, with a polarization $p = (\rho_{\frac{1}{2}\frac{1}{2}} - \rho_{-\frac{1}{2}\frac{1}{2}})$, the asymmetrical term in (7) is merely weighted by p. The polarization is introduced through a density matrix $\rho_{mm'}$, with m, m' being the eigenvalues of the spin component along the z axis.

In both the Ξ and Λ ($\bar{\Xi}$ and $\bar{\Lambda}$) cases we have a particle of spin $\frac{1}{2}$ decaying into a particle of spin $\frac{1}{2}$ and a particle of spin 0. The same relation applies, albeit with different values of α , α_{Ξ} and α_{Λ} respectively, cf. Eq. (2).

The z axis being defined along the direction of the momentum of the decaying particle, we readily obtain from (7) the up-down asymmetry as previously defined, cf. Eq. (3)

$$\frac{N_u - N_d}{N_u + N_d} = \frac{\alpha p}{2} . \quad (2a)$$

In the following, we use the helicity formalism¹⁰⁾ which readily provides some simple relations. In both Ξ and Λ decays, the two independent helicity amplitudes, $a_{\pm \frac{1}{2}}$, are defined according to the helicity of the daughter baryon. The angular part of the full decay amplitude, the modulus square of which gives the angular distribution (7), reads¹⁰⁾

$$A_m(\theta, \phi) = \frac{1}{\sqrt{2\pi}} \left(a_{\frac{1}{2}} D_{m\frac{1}{2}}^{\frac{1}{2}*}(\phi, \theta, -\phi) + a_{-\frac{1}{2}} D_{m-\frac{1}{2}}^{\frac{1}{2}*}(\phi, \theta, -\phi) \right) \quad (8)$$

The normalization chosen is such that

$$|a_{\frac{1}{2}}|^2 + |a_{-\frac{1}{2}}|^2 = 1 . \quad (9)$$

If parity were conserved, the two amplitudes would be equal up to a sign which is determined by the intrinsic properties of the three particles involved. In any of these cases one would have $|a_{\frac{1}{2}}|^2 = |a_{-\frac{1}{2}}|^2$. But with parity violation, calculating (7) from (8), summing over the values of m according to the density matrix of the decaying particle, one readily gets

$$\frac{d\Gamma}{d\theta} = \frac{1}{2} (1 + (|a_{\frac{1}{2}}|^2 - |a_{-\frac{1}{2}}|^2) p \cos \theta) . \quad (10)$$

When summing over the azimuthal angle ϕ only the diagonal elements of the density matrix are retained.

The two helicity amplitudes do not interfere, and one gets in the same way the longitudinal polarization of the daughter baryon,

$$P_L = \rho \cos \theta + |a_{1/2}|^2 - |a_{-1/2}|^2 \quad (11)$$

Hence the mean value of the longitudinal polarization (twice the helicity) of the daughter baryon is equal to the decay asymmetry parameter $\alpha = |a_{1/2}|^2 - |a_{-1/2}|^2$.

We then see how polarization proceeds during the cascade. The Ξ decay gives a Λ with well-defined mean longitudinal polarization α_{Ξ} , and the decay of the Λ serves as an analyzer for this polarization, with an up-down asymmetry with respect to a plane normal to its path of flight. It is readily obtained from (7) and (11), namely

$$\frac{N_u - N_d}{N_u + N_d} = \frac{\alpha_{\Xi} \alpha_{\Lambda}}{2} \quad (12)$$

which, weighted according to the number of Λ originating from Ξ decays, gives (3a).

According to PC-invariance, switching from particle to antiparticle reverses the sign of the asymmetry parameter. Relation (12) is then also true for the $\bar{\Xi} \bar{\Lambda}$ decay chain.

This way we are led to the conclusion that if a sizeable number of $\bar{\Lambda}$'s originate from $\bar{\Xi}$ decays, the value of the up-down asymmetry obtained over the whole $\bar{\Lambda}$ sample should be rather large, and could be used to determine the value of the important parameter $N_{\bar{\Xi}}/N_{\bar{\Lambda}}$. It is an easy and direct signature for the formation of a quark-plasma state having lived long enough for some chemical equilibrium to have been established.

We have shown that the measurement of the longitudinal $\bar{\Lambda}$ -polarization normally absent in hadronic reactions will permit the determination of the abundance ratio $\bar{\Xi}/\bar{\Lambda}$ expected to be a rather characteristic signature for the formation of a new state of hadronic matter, the quark-gluon plasma.

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