Λ^0 nonpolarization: Possible signature of quark matter

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The polarization of the lambda hyperons, produced in proton- and nucleus-induced interactions over a wide range of incident energies and target masses, is examined. The persistence and constancy of the polarization up to the highest energy measured is consistent with the absence of quark-gluon plasma in these reactions. It is suggested that, in ultrarelativistic heavy ion collisions, the formation of quark-gluon plasma in the central region will result in the diminishing of the polarization of central rapidity lambdas.

The strong polarization of singly and doubly strange particles, produced in p-induced interactions, is well established.[1–10] In the case of the Λ^0 hyperon, produced in the elementary—and dominant—production channel $NN \rightarrow KN\Lambda^0$, the polarization (and spin) is carried by the strange quark, the ud quarks forming a spin-zero system. The polarization is thought to be the result of a Thomas precession effect in the quark recombination process, taking into account SU(6) symmetry of hadron wave functions.[11] Another semiclassical model[12] predicts the polarization to be the result of the correlation between the "inherent" transverse momentum and the spin of the s quark, produced by a tunneling (soft) process in the color field, where pertubative quantum chromodynamics (QCD) is not applicable.

In p + p and p + A collisions the number of participating nucleons is not more than the very few interacting hadrons in the primary collisions, while the size of the interaction zone is considerably smaller than the nuclear size, too small to speak of a confined plasma in an extended volume. Furthermore, even the most energetic of the interactions, in which the polarization was measured, does not create the necessary conditions (temperature and energy density) for the formation of quark-gluon plasma. (In p + p interactions at $\sqrt{s}=63$ GeV the energy density is less than 0.5 GeV/fm^3.) It is, therefore, interesting to examine the state of the lambda polarization in ultrarelativistic nucleus-nucleus collisions, where a phase transition to quark matter is conjectured to occur. The speculation that a phase transition may be accompanied by symmetry breaking—reflected in a change of the lambda polarization anisotropy—was first mentioned by Stock.[13] We intend to reconsider this idea in view of the polarization systematics available.

The experimental data on the lambda polarization exhibit the following systematics.

(i) The Λ^0, produced in p + p and p + A collisions, is polarized perpendicularly to the reaction plane. The polarization shows no obvious Feynman x dependence in the range $0.1 \leq x \leq 0.7$, as surmised by the comparison between p + Be data at 400 GeV (Ref. 6) and 300 GeV (Ref. 8). Similar conclusions are drawn from p + p at 360 GeV/c (Ref. 14) and for p + A at 20—28.5 GeV/c (Refs. 4 and 7), where it is found that the polarization is independent of x in the range $0.1 \leq x \leq 0.9$ and $0.2 \leq x \leq 0.8$, respectively, as well as from $\bar{p}+p$ at 22.4 GeV/c (Ref. 15), where it is shown that at $x=0$ the polarizations of both lambda and antilambda have values (of opposite sign) more than two standard deviations from zero.

It is also independent of the beam energy and target mass, as shown in Figs. 1—3. In Fig. 1 we plot the polarization, measured in p + p interactions, as a function of the center of mass energy and for lambda transverse momentum $P_\perp \sim 1.2$ GeV/c. The polarization remains constant in the energy range $10 \leq \sqrt{s} \leq 63$ GeV, with a mean value of -0.38 ± 0.06. In Fig. 2 we show the polarization, measured in p + Be reactions, as a function of the laboratory energy and for $P_\perp \sim 1.2$ GeV/c. We notice a constant polarization in the energy range between 20 and 400 GeV, with a mean value of -0.23 ± 0.05. Finally in Fig. 3 we plot the polarization, measured in p + A reactions in the energy range between 12 and 28.5 GeV and for $P_\perp \sim 1.2$ GeV/c, as a function of the target mass. We observe an almost constant polarization for $2 \leq A_t \leq 200$, with a mean value of -0.22 ± 0.04. We note here that the mean polarization, measured in p + A interactions, is about 35% smaller than the value measured in the elementary N + N interactions at the same $P_\perp$, indicating the influence of other mechanisms in the former case. This point will be discussed later.

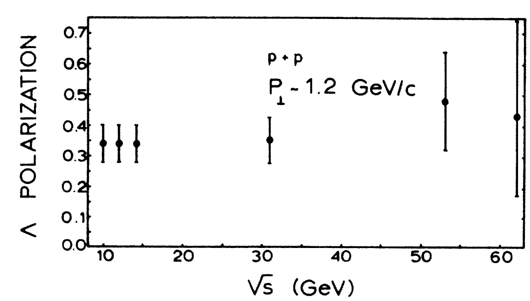

FIG. 1. Lambda polarization at $P_\perp \sim 1.2$ GeV/c as a function of the center of mass energy in p + p interactions. Data are from Refs. 1, 2, and 4.

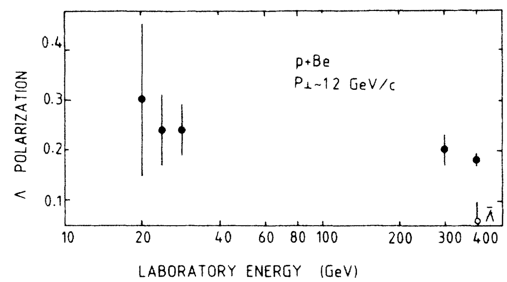

FIG. 2. Lambda polarization at $P_\perp \sim 1.2$ GeV/c as a function of the laboratory energy in p + Be interactions. Note the zero polarization of the antilambda for $P_\perp$ up to 1.2 GeV/c. Data are from Refs. 4, 6, and 8.

(ii) The polarization increases almost linearly with the transverse momentum of the lambda, in the measured transverse momentum range of $0.3 \leq P_\perp \leq 2$ GeV/c.

(iii) The polarization of the antilambda, measured[6] in the p + Be reaction at 400 GeV in the beam direction and for $0.4 \leq p_\perp \leq 1.4$ GeV/c, is zero (Fig. 2). Similarly, the polarization of the lambda in $\bar{\text{p}}$+Ta interactions at 4 GeV/c is found to be zero[13] for $P_\perp$ up to 1 GeV/c.

(iv) The polarization of lambda and antilambda, measured at $\sqrt{s} = 31$ GeV along the beam direction in p + p and $\bar{\text{p}}$+p interactions, respectively, are of equal magnitude and opposite sign.[1] This is in agreement with C invariance in the strong pp interaction and dominant CP invariance in the Λ^0 decay.

From these observations we arrive at the following conclusions, concerning the production mechanism and the polarization of the lambda.

1. The polarization is the result of the elementary, binary hadron-hadron interaction.

2. The leading lambda (antilambda), produced in p- ($\bar{\text{p}}$-) induced interactions in the beam direction ($x > 0$) and exhibiting strong polarization, is made up of two fast valence quarks (antiquarks) of the incoming beam—a spin zero diquark—and a slow sea s ($\bar{s}$) quark. In other words, the leading Λ^0 ($\bar{\Lambda}^0$), is produced via a "direct strangeness exchange" mechanism, whereby the u ($\bar{u}$) quark of the incoming proton (antiproton) is exchanged for an s ($\bar{s}$) quark, as shown in Fig. 4.

3. The lambda (antilambda), produced in $\bar{\text{p}}$-(p-) induced interactions at $x > 0$, does not exhibit any polarization. It is a nonleading particle, created through the recombination of slow sea quarks (antiquarks) and emitted via an evaporationlike process from the hot interaction zone. This we anticipate to be the mechanism of lambda production in the quark-gluon plasma.

We discuss now possible effects which may cause the diminishing of the Λ^0 polarization in A + A collisions.

I. secondary scattering of the leading lambdas with hadrons within the interaction zone;

II. secondary production of lambdas through the $\pi N \to K N \Lambda^0$ channel within the interaction zone;

III. production of lambdas from the quark-gluon plasma, formed in the central rapidity region in ultrarelativistic A + A collisions.

I. Rescattering within the interaction region is not an important effect, since p + A interactions show strong Λ^0 polarization in the energy range of 20–400 GeV and target mass range between 2 and 200 ($\langle p \rangle = -0.23 \pm 0.05$ at $P_\perp \sim 1.2$ GeV/c). The consequence of this effect is already included in the measurements and the values quoted denote the measured *net* polarization. Quantitatively, rescattering of the lambda may cause a reduction of its polarization by less than two standard deviations from the value measured in the elementary pp interaction. It may also displace the distribution of the lambdas with respect to the kinematical locus of the NN interaction in a $P_\perp$ vs rapidity plot. This is most probably what was observed in the $\bar{\text{p}}$+Ta collisions at 4 GeV/c in the $P_\perp$ vs y lambda distribution,[16] where rescattering caused the increase of the effective target mass in the interaction from "p + N" to "p + 13N" in the c.m. (However, at energies such as this close to particle production threshold, it is not easy to clearly differentiate between collective and rescattering effects.)

In the case of A + A collisions, the scarce data[17,18] do not show quantitatively and conclusively increased effects of rescattering on the polarization, despite the fact that the interaction region is greatly enlarged in terms of the number of interacting hadrons and size.

II. πN interactions[19] could become an important source of unpolarized lambdas due to (a) increasing $\pi + A \to \Lambda^0$ cross section with increasing A, and (b) increasing pion-production cross section with energy in

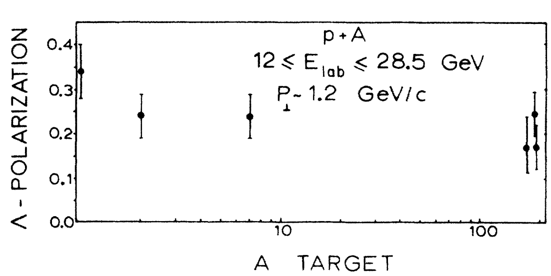

FIG. 3. Lambda polarization at $P_\perp \sim 1.2$ GeV/c as a function of the target mass. Data are from Refs. 3–5 and 7.

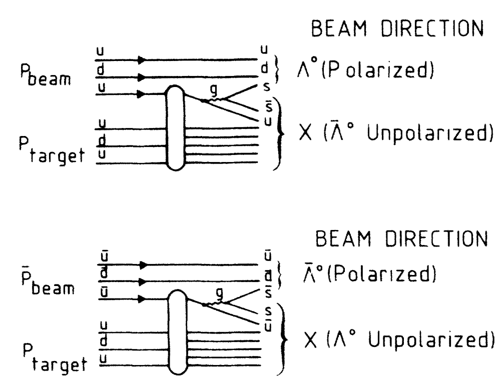

FIG. 4. Kinematics of $\Lambda^0, \bar{\Lambda}^0$ production and polarization in terms of the recombination parton model.

nucleus-nucleus collisions. In the former case the lambda cross section increases as A^a, where $\langle a \rangle = 0.68$ for Feynman x in the range $0 \le x \le 0.6$.[20] In the latter case, the pion cross section in A + A reactions increases almost monotonically with incident energy.[21,22] However, data from He + A (Ref. 23) and A + A (Ref. 18 and 24) interactions at 4.5 GeV/c show the following.

i. The mean negative pion multiplicity exhibits a slow target mass dependence, $\langle n_- \rangle = A_t^a$ ($a = 0.3$), for intermediate rapidity events, $0 \le y \le 2.3$.

ii. The mean negative pion multiplicity is independent of the target mass for $P_\perp > 0.4$ GeV/c.

iii. The mean negative pion transverse momentum decreases with increasing A_t for central events.

iv. The ratio of the mean lambda multiplicity to the negative pion multiplicity, $\langle n_{\Lambda^0} \rangle / \langle n_- \rangle$, is independent of the target mass for central events.

We may infer from these systematics that the majority of the lambdas, produced via secondary πN interactions, should lie beyond the free NN phase space kinematical limit and mainly in the low laboratory momenta. They can, hence, be excluded from the polarization analysis of the lambdas of interest.

Recent data on Λ^0 polarization from A + A interactions indicate that, despite the aforesaid destructive effects, the polarization still exists, at energies, however, much below the quark matter threshold:

(i) In ^{40}Ar + KCl reactions at 1.8 GeV/nucleon,[17] an average Λ^0 polarization of -0.10 ± 0.05 is reported. Although this value is very close to zero, it should be noted that the average transverse momentum of the hyperons was less than 0.5 GeV/c, and that even p + p interactions exhibit similarly small polarization at such low $P_\perp$ values.[2] Furthermore, only few of the analyzed lambdas were found within the binary NN$\rightarrow$KNΛ^0 kinematical limit, indicating that, in the estimation of the polarization, the main contribution came from lambdas of secondary interactions and rescattered lambdas with zero or reduced polarization.

(ii) In A + A reactions at 4.5 GeV/c,[18] average values for (aP_{Λ^0}) of -0.018 ± 0.14 and -0.23 ± 0.13 are reported from the total samples of identified intermediate rapidity lambdas and for transverse momenta $P_\perp < 0.5$ and $P_\perp \ge 0.5$ GeV/c, respectively. The zero polarization corresponds to a very small average transverse momentum $\langle P_\perp \rangle \sim 0.3$ GeV/c, while the nonzero value corresponds to an average transverse momentum $\langle P_\perp \rangle \sim 0.7$ GeV/c. It should be also noted that in the latter measurement 80% of the lambdas are found within the kinematical limits of the free NN$\rightarrow$KNΛ^0 production channel, with maximum transverse momentum $P_\perp < 1.0$ GeV/c, while the remaining 20% outside the limits may arise from rescattering and secondary interactions.

The results of these two measurements are shown in Fig. 5, together with polarization data from p + A interactions.[5–7] We point out that the polarization data from p + A collisions at $P_\perp \sim 0.5$ GeV/c have comparable values to those in A + A collisions and that all low $P_\perp$ measurements show practically zero polarization as expected. We may then conclude that the available—although scarce—polarization data from A + A interactions, below the quark-gluon plasma threshold, indicate the existence of nonzero lambda polarization.

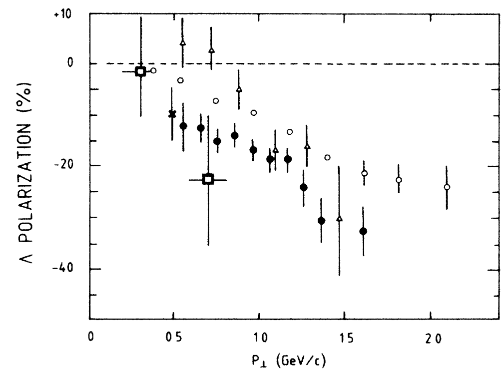

FIG. 5. Percent lambda polarization versus the transverse momentum in p + A and A + A interactions. Data are from Ref. 5: p + Ir (filled circles); Ref. 6: p + Be (open circles); Ref. 7: p+Pl (triangles); Ref. 17: Ar + KCl (cross); and Ref. 18: A + A (open squares). The horizontal error bar denotes the uncertainty in the average $P_\perp$ value.

III. In the case of quark-gluon plasma formation in ultrarelativistic nucleus-nucleus collisions, the lambdas of interest are produced in and emitted from the central rapidity zone, which is fairly well separated ($\Delta y = \pm 1-2$) from the two fragmentation regimes.[25] These lambdas could be created through the recombination of independent, slow sea q and s quarks (the "popcorn" model[26]), or by combining a diquark and a quark, (the "diquark" model[27]), and will be emitted via an evaporationlike process. In most respects, the mechanism of creation and the properties of the "plasma lambdas" are the same as those of the lambdas (antilambdas) produced, respectively, in $\bar{\text{p}}$-(p-) induced reactions at Feynman $x > 0$ and in the $e + e^-$ annihilation process. In addition, the color field in the quark-gluon plasma could possess transverse momentum, which would provide transverse momentum to the $s\bar{s}$ quarks, thereby destroying the—polarization producing—correlation between the "inherent" transverse momentum and the spin of the s quark (arising from local conservation in the string force field[12]). The plasma-created lambdas are, therefore, expected to show zero polarization.

Hence, if the polarization of central rapidity lambdas continues to exist at energies where nuclear transparency is clearly established and up to the quark deconfinement threshold (although sharp thresholds are not intuitively expected), then a total or significant reduction of the polarization at a higher energy shall constitute a signature for the formation of quark-gluon plasma in the central zone and the onset of a phase transition.

In this discussion we rely on the assumption that quark-gluon plasma does not contain substantial "primordial" hadronic matter. In the opposite case, not only will there be NN-created (polarized) lambdas, but more seriously, this hadronic matter will become the seed for further hadronization of the quark-gluon plasma, resulting in fast cooling before it has sufficient time to reach local thermal and chemical equilibrium. Calculations[28] have shown that increased strangeness production is expected in the thermally and chemically equilibrated quark-gluon phase, as compared to the hadron phase in the central rapidity region, for reasonable values of the temperature, $120 \leq T \leq 160$ MeV, the mass of the s quark, $150 \leq M_s \leq 280$ MeV, and the density, $\rho/\rho_0 < 2$:

$$\langle n_s(q \text{ phase})\rangle / \langle n_s(h \text{ phase})\rangle > 4 .$$

Therefore, the plasma-created lambdas will by far exceed those produced by the remnants of hadronic matter in the plasma region. It should be pointed out, however, that it is crucial to separate the central rapidity plasma from the target (projectile) fragmentation regimes (where plasma may also be formed), so as not to combine the plasma-created lambdas with the abundant NN-produced ones.

Summarizing, we expect the observed polarization of lambdas, emitted from the plasma (central) region, to be zero or significantly smaller than the polarization measured in the same central region in A + A collisions below the quark matter threshold. Of course, the polarization of the antilambdas will remain zero for all energies and all Feynman x, since they are created only from the sea antiquarks. It should be noted also that the polarization of the lambdas, emitted from the two fragmentation regions which carry almost entirely the baryonic number, would still exist but possibly somewhat reduced, since quark-gluon plasma may be formed in these regions as well.

It will be worthwhile to measure the lambda polarization in A + A collisions as a function of the incident energy in the range between 10 and 200 GeV/nucleon and over a wide $P_\perp$ range ($0.5 \leq P_\perp \leq 2$ GeV/c). These measurements, together with searches for other proposed quark-gluon plasma signatures,[29] will shed light on the fundamental multidisciplinary questions of quark deconfinement, phase transition, and eventually the formation of cosmos.

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