

Λ^0 polarization as a probe for production of deconfined matter in ultrarelativistic heavy-ion collisions

Alejandro Ayala,¹ Eleazar Cuautle,¹ Gerardo Herrera,² and Luis Manuel Montaño²¹*Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Apartado Postal 70-543, México Distrito Federal 04510, México.*²*Centro de Investigación y de Estudios Avanzados, Apartado Postal 14-740, México Distrito Federal 07000, México*

(Received 9 October 2001; published 9 January 2002)

We study the polarization change of Λ^0 's produced in ultrarelativistic heavy-ion collisions with respect to the polarization observed in proton-proton collisions as a signal for the formation of a quark-gluon plasma (QGP). Assuming that, when the density of participants in the collision is larger than the critical density for QGP formation, the Λ^0 production mechanism changes from recombination type processes to the coalescence of free valence quarks, we find that the Λ^0 polarization depends on the relative contribution of each process to the total number of Λ^0 's produced in the collision. To describe the polarization of Λ^0 's in nuclear collisions for densities below the critical density for the QGP formation, we use the DeGrand-Miettinen model corrected for the effects introduced by multiple scattering of the produced Λ^0 within the nuclear environment.

DOI: 10.1103/PhysRevC.65.024902

PACS number(s): 13.88.+e, 13.75.Ev

I. INTRODUCTION

The study of the kind of matter produced during nuclear collisions at relativistic and ultrarelativistic energies has become the subject of an increasing experimental and theoretical effort during the last years. The main drive for such study is the expectation that a phase transition, from ordinary nuclear matter to a quark gluon plasma (QGP), should be observed when conditions of sufficiently high baryonic densities and/or temperatures are achieved during the collision. In order to identify this phase transition, a number of experimental observables, such as J/Ψ suppression, strangeness enhancement, fluctuations in particle ratios, flow patterns, etc., have been proposed [1]. At the same time, it has also been recognized that no single signal can, by itself, provide clear cut evidence for the existence of the QGP and that it is only through the combined analysis of all possible signals that the production of such state of matter can be firmly established. This realization has stimulated the search for new probes to aid in the understanding of the properties of the complex environment produced in heavy-ion collisions at high energy.

One of the first proposed signatures to unveil the production of a QGP in relativistic nucleus-nucleus collisions was to study the change in the polarization properties of Λ^0 hyperons as compared to that observed in proton-proton collisions [2,3]. At the same time, no quantitative model has been proposed to realize such an idea in this kind of environment.

Recall that, in high-energy proton-induced reactions, the produced hyperons exhibit a strong polarization. Among the hyperons, the Λ^0 plays a special role due to its rather simple spin structure within the static quark model and to the fact that its self-analyzing main decay mode into $p + \pi^-$, makes polarization measurements experimentally feasible.

For proton-induced reactions, it has long been established [4] that the spin of the Λ^0 is carried by the produced s -quark and that the u and d quarks can be thought of as being coupled into a diquark with zero total angular momentum

and isospin. However, despite the wealth of experimental information and theoretical insight accumulated during the last three decades, a complete understanding of the hyperon polarization mechanism is still missing, mainly because, as is currently believed, this mechanism has its origin in the recombination processes whose nature belongs to the realm of non-perturbative phenomena.

Nonetheless, a quantitative description of hyperon polarization properties in proton- and meson-induced reactions has been attained by a semiclassical model put forward by DeGrand and Miettinen [5] (see also Ref. [6]). In this model, the hyperon polarization is due to a Thomas precession effect during the quark recombination process of slow (sea) s quarks and fast (valence) ud diquarks.

In the case of relativistic nucleus-nucleus collisions, the expectation is that, Λ^0 's coming from the zone where the critical density for QGP formation has been achieved, are produced through the coalescence of independent slow sea u , d , and s quarks and are emitted via an evaporationlike process. Consequently, these *plasma* created Λ^0 's should show zero polarization [3].

An accurate estimate of the change of the Λ^0 polarization observed in high-energy heavy-ion collisions as compared to proton-proton reactions requires knowledge of the relative contribution to the total Λ^0 yield both from the plasma zone and from regions where the critical density for QGP formation has not been reached. Moreover, since those Λ^0 's produced in these latter regions experience multiple scattering with the surrounding nuclear environment, the final polarization value should reflect the effects introduced by these processes.

In this paper, we propose a method to extract information from Λ^0 polarization measurements in ultrarelativistic heavy-ion collisions as a means to determine the production of a QGP. We study a model where the Λ^0 's produced in the zone where the critical density for QGP formation is reached are unpolarized while the Λ^0 's produced in the rest of the reaction zone are produced polarized, in the same way as

they are in free nucleon-nucleon reactions. We use the DeGrand-Miettinen model (DMM) to describe the polarization of these latter Λ^0 's. The effects on the polarization arising from multiple scattering are introduced in terms of a sequential model of collisions [7,8]. We also discuss possible depolarization effects introduced by spin-flip interactions of Λ^0 within the nuclear medium.

The work is organized as follows. In Sec. II we briefly review the DMM for the polarization of hyperons produced in proton-proton reactions. In Sec. III, we discuss the mechanisms that can induce a change in the polarization of hyperons produced in high-energy nucleus-nucleus reactions as compared to proton-proton collisions. We account for these changes in terms of a sequential model of collisions. To illustrate our results, we introduce the appropriate parameters which we extract from the existing (though scarce) data on Λ^0 -nucleon interactions. In Sec. IV, we present our model for the production of Λ^0 coming from the regions in the reaction zone with a density of participants below and above the critical density for QGP formation. We show that the polarization of these Λ^0 's depends on the relative contribution of each of the above production mechanisms to the total Λ^0 yield. We also include the modifications to the polarization introduced by multiple scattering of Λ^0 's in those regions with a density of participants below the critical density for QGP formation. Armed with such expression for the Λ^0 polarization in high-energy nucleus-nucleus reactions, we apply the formalism to study ^{208}Pb - ^{208}Pb collisions and draw quantitative conclusions about the Λ^0 polarization behavior as a function of both its transverse momentum and impact parameter of the reaction. We finally summarize and conclude in Sec. V. In what follows, we present the expressions in terms of quantities in the laboratory frame.

II. Λ^0 POLARIZATION IN THE DEGRAND-MIETTINEN MODEL

The Λ^0 hyperon has spin $S=1/2$. Its preferred decay mode $\Lambda^0 \rightarrow p + \pi^-$ (64% branching ratio) is mediated by the weak interaction, therefore, the information from the distribution of its decay products can be used to determine the orientation of its spin. Since the discovery of a substantial Λ^0 transverse polarization in high-energy, hadron-nucleon [9], nucleon-nucleon [10], and nucleon-nucleus [11] reactions, a large amount of theoretical and experimental activity has been devoted to understanding the origin of such polarization. The fact that Λ^0 's were produced with a significant polarization while $\bar{\Lambda}^0$'s were unpolarized was, at first, surprising. Several models were proposed to explain that phenomena. One of the most successful is the DMM [5]. In this semiclassical model, the Λ^0 polarization results from a Thomas precession of the spin of the s quark in the recombination process. The u and d quarks are assumed to form a diquark in a state with total angular momentum $J=0$ (and isospin $I=0$) and thus, the s -quark is entirely responsible of the spin of the Λ^0 .

The recombining quarks in the projectile must also carry a transverse momentum given, approximately by half of the transverse momentum of the outgoing hadron, while the

other half is carried by the s quark. Since the x distribution of the (sea) s quarks peaks at very low values and is very steep, a Λ^0 must get most of its longitudinal momentum from the valence ud -diquark momentum. In the process, the s quark is, on average, accelerated but, since its transverse momentum is different from zero, the force \mathbf{F} felt by the quark is not parallel to its velocity $\boldsymbol{\beta}$, giving rise to Thomas precession, characterized by a frequency $\boldsymbol{\omega}_T$ given by

$$\boldsymbol{\omega}_T = \left(\frac{\gamma}{\gamma+1} \right) \mathbf{F} \times \boldsymbol{\beta}, \quad (1)$$

where γ is the Lorentz gamma factor. When this frequency is used to account for the spin-orbit term in the Hamiltonian for computing the scattering amplitudes to produce Λ^0 's with spin oriented along and opposite to the normal of the production plane, it gives rise to a negative polarization, since it is more likely that the (sea) s quark is accelerated than decelerated to recombine into a Λ^0 .

Notice that in the model, the polarization asymmetry arises as a consequence of a strong momentum ordering where the s quark is (on average) slow and the ud diquark is (on average) fast. This ordering does not happen when the recombination involves only sea s , u , or d quarks or anti-quarks, as is the case of antihyperon production or, more important to our purposes, a Λ^0 originated from a QGP.

The polarization of a Λ^0 in proton-proton collisions is given in the DMM by

$$\mathcal{P}^{\text{REC}} = - \frac{12}{\Delta x_0 M^2} \left(\frac{1-3\xi(x)}{[1+3\xi(x)]^2} \right) p_T, \quad (2)$$

where

$$M^2 = \left[\frac{m_D^2 + p_{TD}^2}{1-\xi(x)} + \frac{m_s^2 + p_{Ts}^2}{\xi(x)} - m_{\Lambda^0}^2 - p_T^2 \right] \quad (3)$$

with m_D , p_{TD} (m_s , p_{Ts}) the mass and transverse momentum of the ud diquark (s quark), m_{Λ^0} and p_T the mass and transverse momentum of the Λ^0 , Δx_0 a distance scale, on the order of the proton radius, characterizing the recombination length scale, and $\xi(x) = x_s/x$ the ratio of the longitudinal momentum fraction of the s quark to the longitudinal momentum fraction of the Λ^0 with respect to the beam proton.

To give a quantitative description for the polarization, DeGrand and Miettinen take a linear parametrization for $\xi(x)$ such that

$$\xi(x) = \frac{1}{3}(1-x) + 0.1x, \quad (4)$$

which represents a reasonable interpolation between the values for ξ near $x=0$, where the distribution for all flavors is roughly equal in shape, and near $x=1$, where the distribution of sea and valence quarks is small, the former being even smaller than the latter. Using this parametrization, DeGrand and Miettinen obtain a good description of experimental data [5]. If, on the other hand, use is made of a recombination model [12] and $\xi(x)$ explicitly computed, the results for the

polarization do not show a drastic change. We therefore use here, for the sake of simplicity, the linear parametrization for $\xi(x)$ given by Eq. (4). To complete the overall parametrization of \mathcal{P}^{REC} , we also take $m_D=2/3$ GeV, $m_s=1/2$ GeV and $p_{T_s}^2=p_{TD}^2=(1/4)p_T^2+\langle k_T^2 \rangle$ with $\langle k_T^2 \rangle=0.25$ GeV² [5].

III. DEPOLARIZATION EFFECTS IN NUCLEUS-NUCLEUS COLLISIONS

In the case of nucleus-nucleus collisions, the effects that can possibly produce a diminishing of the Λ^0 polarization have been enumerated in Ref. [3]. These are (i) secondary Λ^0 's produced by pion-nucleon scattering, (ii) Λ^0 production from a QGP, and (iii) secondary scattering of leading Λ^0 's with nucleons within the interaction zone.

Though production of Λ^0 's by pion-nucleon scattering becomes important in collisions, of large nuclei at high energy, due to both, an increase of the pion-nucleon and the pion production cross sections with increasing atomic number at high energies, these Λ^0 's are mainly produced beyond the free nucleon-nucleon phase space kinematical limit and at low (laboratory) momenta. It is thus possible to set kinematical constraints in the reconstruction of these Λ^0 's and therefore exclude them from the polarization analysis. Thus, we do not further consider this effect. We postpone the discussion on the polarization modification of Λ^0 's originating from a QGP to Sec. IV. Here, we concentrate on the effects introduced by secondary scattering of Λ^0 's with nucleons in the zone where the density of participants is below the threshold for a QGP formation.

Secondary scattering within nuclear matter is an important effect in high-energy nucleus-nucleus collisions. It is responsible for the transverse spectrum broadening of produced particles and for the longitudinal momentum loss of nucleons, which is related to the degree of stopping in the reaction.

Since at high energies, the trend for the existing (though scarce) data on free Λ^0 -nucleon interactions indicates that elastic scattering dominates the total cross section [13], we concentrate on describing the effects on the Λ^0 polarization by these kind of collisions. Secondary elastic scattering of Λ^0 's with nucleons can influence the final polarization measurements by producing (a) a shift in the Λ^0 longitudinal momentum, (b) a shift in the Λ^0 transverse momentum, and (c) a flip in the original Λ^0 spin direction. We proceed to quantitatively discuss each one of these effects.

A. Longitudinal momentum shift

Multiple elastic scattering can be cast in terms of a sequential model [7,8], where it is assumed that the average energy of a particle after $n+1$ collisions is given in terms of the average energy after n collisions by

$$\langle E_{\Lambda^0} \rangle_{n+1} = (1-I) \langle E_{\Lambda^0} \rangle_n, \quad (5)$$

where I is the inelasticity coefficient [14]. In the high energy limit ($p \gg m_{\Lambda^0}$)

$$\langle E_{\Lambda^0} \rangle_n \simeq \langle p_{\Lambda^0} \rangle_n = p \langle x \rangle_n, \quad (6)$$

where p is the initial momentum value of the nucleon that produced (through recombination) the Λ^0 and x the fraction of the initial longitudinal Λ^0 momentum to the nucleon longitudinal momentum. Equations (5) and (6) can be combined to find the average value of x after n collisions as

$$\langle x \rangle_n = (1-I)^n x. \quad (7)$$

We now proceed to find the average value $\langle x(z,b) \rangle$, after the produced Λ^0 has traveled a longitudinal distance z , in collisions with impact parameter b . Recall that the distribution probability $P_n(z,b)$ for n collisions in reactions with impact parameter b is Poissonian, that is,

$$P_n(z,b) = \frac{1}{n!} \bar{N}^n(z,b) e^{-\bar{N}(z,b)}, \quad (8)$$

with

$$\bar{N}(z,b) = \sigma_{\Lambda^0 N}^{\text{tot}} T_A(z,b/2), \quad (9)$$

being the average number of collisions after the Λ^0 has traveled a longitudinal distance z , given in terms of the total Λ^0 -nucleon cross section, which we take as $\sigma_{\Lambda^0 N}^{\text{tot}} \simeq 25$ mb and

$$T_A(z,s) = \int_{-z/2}^{z/2} \rho_A(z',s) dz' \quad (10)$$

being the average nucleon density per unit area in the transverse plane with respect to the collision axis. Notice that the argument of the function T_A in Eq. (9) referring to the location of the trajectory of the Λ^0 in the transverse planes has been taken as the geometrical average in these planes.

Therefore, $\langle x(z,b) \rangle$ is given by

$$\langle x(z,b) \rangle = x e^{-\bar{N}(z,b)} \sum_{n=0}^{\infty} \frac{(1-I)^n}{n!} \bar{N}^n(z,b) = x e^{-I \bar{N}(z,b)}. \quad (11)$$

It can be shown [8] that $I = \lambda/2$, where

$$\lambda \simeq \frac{\sigma_{\Lambda^0 N}^{\text{inel}}}{\sigma_{\Lambda^0 N}^{\text{tot}}}, \quad (12)$$

with $\sigma_{\Lambda^0 N}^{\text{tot}}$ and $\sigma_{\Lambda^0 N}^{\text{inel}}$ the total and inelastic Λ^0 -nucleon cross sections, respectively. Although these should be taken as the cross sections in nuclear matter, such information has not been experimentally obtained up until now. Nevertheless, from data at low and intermediate energies, it is known that the free cross sections follow the behavior of the corresponding nucleon-nucleon cross sections [15]. Assuming that this is also the case within nuclear matter, we extrapolate the existing data on free Λ^0 -nucleon interactions to high energies [13] and obtain $\lambda \simeq 0.4$ which is consistent with the corresponding value obtained for nucleon-nucleon collisions within nuclear matter [8].

B. Transverse momentum shift

Let $Q(\mathbf{s}_f, \mathbf{s}_i, z)$ be the probability that the produced Λ^0 ends up traveling in the direction \mathbf{s}_f after traveling a longitudinal distance z , having been produced moving in direction \mathbf{s}_i . Let $q_n(\mathbf{s}_f, \mathbf{s}_i)$ be the probability that the Λ^0 ends up traveling in the direction \mathbf{s}_f after n collisions with nucleons, having been produced moving in direction \mathbf{s}_i . The vectors \mathbf{s}_f and \mathbf{s}_i can be thought of as two-dimensional unit vectors, given the isotropy of the angular distribution in each collision.

It is easy to show [16] that the explicit expression for $q_n(\mathbf{s}_f, \mathbf{s}_i)$ is

$$q_n(\mathbf{s}_f, \mathbf{s}_i) = \left(\frac{1}{n\pi\Gamma^2} \right) e^{-(\mathbf{s}_f - \mathbf{s}_i)^2/n\Gamma^2}, \quad (13)$$

where the distribution is taken as Gaussian and for the ease of the calculations, the range of each component of \mathbf{s}_f and \mathbf{s}_i is taken as $[-\infty, \infty]$. Γ is the average dispersion angle in each collision. We emphasize that the expression in Eq. (13) is valid for small dispersion angles. Since the distribution probability for n collisions is given by Eq. (8), $Q(\mathbf{s}_f, \mathbf{s}_i, z)$ is given as

$$Q(\mathbf{s}_f, \mathbf{s}_i, z) = \sum_{n=0}^{\infty} P_n(z, b) q_n(\mathbf{s}_f, \mathbf{s}_i). \quad (14)$$

The average change in the Λ^0 momentum direction is computed from the r.m.s value of the total dispersion angle, α , given by

$$\alpha = \sqrt{\int d^2s s^2 Q(\mathbf{s}, z)} = \Gamma \sqrt{\bar{N}(z, b)}, \quad (15)$$

where $\mathbf{s} = \mathbf{s}_f - \mathbf{s}_i$, since Q depends only on such difference. It is now a simple matter to express the average value of the Λ^0 transverse momentum after having traversed a longitudinal distance z within the nuclear medium, as

$$\langle p_T(z, b) \rangle = (\sqrt{p_{\Lambda^0}^2 - p_T^2} \sin \alpha + p_T \cos \alpha) e^{-I\bar{N}(z, b)}, \quad (16)$$

where the factor $e^{-I\bar{N}(z, b)}$ comes from considering the average change in the magnitude of the Λ^0 momentum.

In the high-energy limit $\cos \alpha \approx 1$, and we can safely ignore the first term in Eq. (16), writing

$$\langle p_T(z, b) \rangle \approx p_T e^{-I\bar{N}(z, b)} \cos\{\Gamma \sqrt{\bar{N}(z, b)}\}, \quad (17)$$

where p_T is the transverse momentum that the Λ^0 carried originally and we have used Eq. (15). Γ can be estimated using the data on angular distributions of free Λ^0 -nucleon elastic scattering. For intermediate energies with $300 \text{ MeV}/c \leq p_{\Lambda^0} \leq 1500 \text{ MeV}/c$, such data exists and Γ can be read off from the parametrization of the angular distribution for $p_{\Lambda^0} > 800 \text{ MeV}/c$ in terms of Legendre polynomials with $l=1, 2, 3$ in Ref. [17]. By doing so it is easy to get that $\Gamma \approx 1.2 \text{ rad.}$, which represents a large value. However, we expect that at higher energies, elastic dispersion takes place with smaller values of Γ . In fact, as the energy of

the produced Λ^0 increases from about 1 GeV to a few tenths of GeV, its deBroglie wavelength $\bar{\lambda}$ decreases from about 0.1 fm to 0.01 fm. Since the transverse size d of the scatterers (nucleons) is about 1 fm, we can estimate that [16] $\Gamma \sim \bar{\lambda}/d = 0.01$. Hereafter, we use this value of Γ in our calculations.

C. Spin flip

The existing data on Λ^0 production by meson-induced reactions on light nuclei [18] show that the effects on the Λ^0 polarization produced by final state interactions (Λ^0 -nucleon scattering) are small. Since, within a light nucleus, the average number of collisions experienced by a produced Λ^0 is $\bar{N} < 1$, it is to be expected that the effects, if any, reflect the depolarization involving the spin interactions.

Let us first note [19] that the spin-orbit interactions cannot contribute to Λ^0 depolarization, given that this interaction is parity-conserving. Since depolarization requires spin-flip, the only interaction capable to produce it is the spin-spin interaction.

To quantify the degree of depolarization in a single Λ^0 -nucleon collision, it is customary to introduce the polarization transfer coefficient [20] D , which, in the case of forward scattering, expresses the final polarization \mathcal{P}' in terms of the original polarization \mathcal{P} as

$$\mathcal{P}' = D \mathcal{P}. \quad (18)$$

In a multiple scattering scenario, such as the one considered here, the average depolarization due to two-body Λ^0 -nucleon interactions can be written as

$$\langle \mathcal{P}'(z, b) \rangle = \mathcal{P} \sum_{n=0}^{\infty} P_n(z, b) D^n = \mathcal{P} e^{-\bar{N}(z, b)(1-D)}. \quad (19)$$

Assuming that the spin-spin interactions are isotropic, D can be expressed as

$$D = \frac{|\bar{V}|^2 + |S_{\Lambda}|^2 + |S_N|^2 - |\Delta|^2}{|\bar{V}|^2 + |S_{\Lambda}|^2 + |S_N|^2 + 3|\Delta|^2}, \quad (20)$$

where \bar{V} , S_{Λ} , S_N , and Δ represent the amplitudes for the spin-independent, Λ^0 spin-orbit, nucleon spin-orbit and spin-spin interactions, respectively, appearing in the expression for the two-body Λ^0 -nucleon potential [21].

The above parameters can be reasonably constrained at low energies (a few MeV's) from the spectral analysis of hypernuclei levels [22], however, no further experimental data exists at higher energies. Nevertheless, it is clear that, when in the range of energies of interest, the parameters appearing in Eq. (20) are measured, D can be considered to be a constant smaller than unity. Therefore, for a given impact parameter, the spin-flip interactions have a simple effect on the depolarization of Λ^0 's produced in nucleus-nucleus collisions. For the purposes of this work and until experimental information becomes available, we will omit these effects from the analysis.

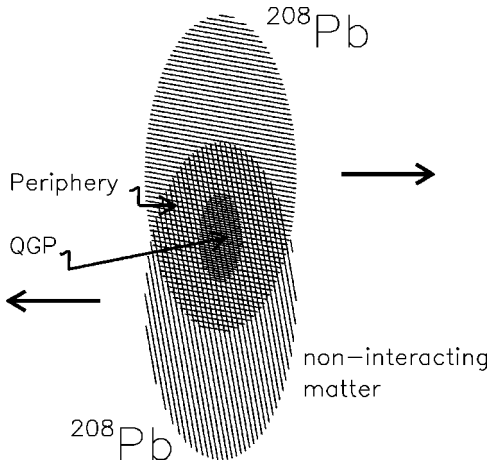


FIG. 1. The reaction $^{208}\text{Pb}-^{208}\text{Pb}$ and the regions where Λ^0 's may be produced. In the QGP, Λ^0 's originate from the QCD processes $q\bar{q} \rightarrow s\bar{s}$ and $g g \rightarrow s\bar{s}$. In the periphery Λ^0 's are produced by recombination.

IV. Λ^0 PRODUCTION AND POLARIZATION IN ULTRARELATIVISTIC HEAVY-ION COLLISIONS

In a QGP the $s\bar{s}$ pair production can be reasonably well described by the lowest order QCD processes $q + \bar{q} \rightarrow s + \bar{s}$ and $g + g \rightarrow s + \bar{s}$ [23]. To simplify the analysis, we assume that in this environment, the Λ^0 's are the sole products of the subsequent s -quark recombination. The enhancement of strangeness production in a QGP plasma leads to an enhancement of hyperon production. However, Λ^0 formation in this environment should not show a strong ordering for the momenta of any of the u , d , or s quarks, and consequently, according to the DMM, these Λ^0 's should not be polarized [24].

On the other hand, in the interaction region where nucleon-nucleon collisions take place but the density is not high enough to deconfine quarks and gluons, Λ^0 's would be produced by recombination of (ud) diquarks, coming from the interacting nucleons and, s quarks coming from the sea. The total cross section σ_{Λ^0} for Λ^0 production is then given by these two components

$$\sigma_{\Lambda^0} = \sigma_{\Lambda^0}^{\text{REC}} + \sigma_{\Lambda^0}^{\text{QGP}}. \quad (21)$$

The regions where the two distinct Λ^0 production mechanisms take place during the collision are shown schematically in Fig. 1.

A. Λ^0 production from recombination

To describe Λ^0 production by recombination we write the production cross section at impact parameter b in the collision of ions A and B as

$$\frac{1}{\sigma_{\Lambda^0}^{\text{NN}}} \frac{d^2 \sigma_{\Lambda^0}^{\text{REC}}}{d^2 b} = T_{AB}(b), \quad (22)$$

where $\sigma_{\Lambda^0}^{\text{NN}}$ is the Λ^0 production cross section in nucleon-nucleon collisions, which we take as $\sigma_{\Lambda^0}^{\text{NN}} = 3.2$ mb [25] and $T_{AB}(b)$ is given by

$$T_{AB}(z, b) = \int d^2 s T_A(z, \mathbf{s}) T_B(z, \mathbf{s} - \mathbf{b}), \quad (23)$$

with T_A and T_B given in terms of Eq. (10), extending the limits of integration over z in Eq. (10) to $[-\infty, \infty]$. For $\rho_A(\mathbf{r})$ we use the standard Woods-Saxon density profile

$$\rho_A(\mathbf{r}) = \frac{\rho_0}{1 + e^{(r-R_A)/a}}, \quad (24)$$

with $R_A = 1.1A^{1/3}$ fm, $a = 0.53$ fm and ρ_0 fixed by normalization

$$\int \rho_A(\mathbf{r}) d^3 r = A, \quad (25)$$

giving $\rho_0 = 0.17$ fm $^{-3}$ for ^{208}Pb .

We assume that each subcollision produces final state particles in the same way as in free nucleon reactions and thus we can estimate the number of Λ^0 's produced by recombination from Eq. (23). However, in order to exclude the zone where the density of participants n_p is above the critical density n_c to produce a QGP, we rewrite Eqs. (23) and (22) as

$$\frac{d^2 \sigma_{\Lambda^0}^{\text{REC}}}{d^2 b} = \sigma_{\Lambda^0}^{\text{NN}} \int T_B(\mathbf{b} - \mathbf{s}) T_A(\mathbf{s}) \theta[n_c - n_p(\mathbf{s}, \mathbf{b})] d^2 s, \quad (26)$$

where $n_p(\mathbf{s})$ is the density of participants at the point \mathbf{s} in the transverse plane and θ is the step function.

The density of participants per unit transverse area during the collision of nucleus A on nucleus B , at an impact parameter vector \mathbf{b} , has a profile given by [26]

$$n_p(\mathbf{s}, \mathbf{b}) = T_A(\mathbf{s}) [1 - e^{-\sigma_{NN} T_B(\mathbf{s} - \mathbf{b})}] + T_B(\mathbf{s} - \mathbf{b}) [1 - e^{-\sigma_{NN} T_A(\mathbf{s})}], \quad (27)$$

where σ_{NN} is the nucleon-nucleon inelastic cross section which we take as $\sigma_{NN} = 32$ mb. The total number of participants N_p at impact parameter b is

$$N_p(b) = \int n_p(\mathbf{s}, \mathbf{b}) d^2 s. \quad (28)$$

Following the reasoning in Ref. [26], we choose $n_c = 3.3$ fm $^{-2}$, which results from the observation of a substantial reduction of the J/ψ yield in Pb - Pb collisions at the SPS. Figure 2 shows $d^2 \sigma_{\Lambda^0}^{\text{REC}} / d^2 b$ (dashed line) as a function of b , computed from Eq. (26) for the case of Pb-Pb collisions.

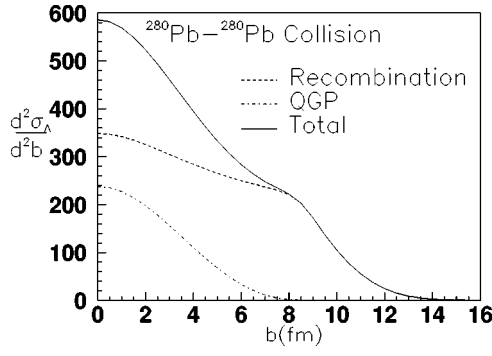


FIG. 2. Λ^0 production as a function of the impact parameter b within the QGP (dashed-dotted line) for $c=0.005$ and in the periphery (dashed line). The solid line represents the total Λ^0 production.

B. Λ^0 production from a QGP

The average number of strange quarks produced in a QGP scales with the number of participants N_p^{QGP} in the collision roughly as [27]

$$\frac{\langle s \rangle}{N_p^{\text{QGP}}} = c N_p^{\text{QGP}}. \quad (29)$$

Assuming for the sake of simplicity that, as a result of hadronization, only Λ^0 's are obtained from these produced s quarks, we can estimate the number of Λ^0 's originating in the QGP, N_p^{QGP} , as a function of the impact parameter is given, using Eq. (28), as

$$N_p^{\text{QGP}}(b) = \int n_p(\mathbf{s}, \mathbf{b}) \theta[n_p(\mathbf{s}, \mathbf{b}) - n_c] d^2 s. \quad (30)$$

The proportionality constant c in Eq. (29) can be read off from Fig. 5(a) in Ref. [27]. Depending on the precise value of α_s and for $^{208}\text{Pb}-^{208}\text{Pb}$ collisions, c is found in the range

$$0.001 \leq c \leq 0.005. \quad (31)$$

Therefore, we take Eq. (29) as representing the behavior of the differential cross section, $d^2 \sigma_{\Lambda^0}^{\text{QGP}}/d^2 b$, namely,

$$\frac{d^2 \sigma_{\Lambda^0}^{\text{QGP}}}{d^2 b} = c [N_p^{\text{QGP}}(b)]^2. \quad (32)$$

Figure 2 shows $d^2 \sigma_{\Lambda^0}^{\text{QGP}}/d^2 b$ (dashed-dotted line) as a function of b , computed from Eq. (32) for the case of Pb-Pb collisions. Shown is also the sum $d^2 \sigma_{\Lambda^0}^{\text{REC}}/d^2 b + d^2 \sigma_{\Lambda^0}^{\text{QGP}}/d^2 b$ (solid line) for the same system.

C. Λ^0 polarization

Recall that the Λ^0 polarization asymmetry \mathcal{P} is defined as the difference between the number of Λ^0 's produced with spin pointing along and opposite to the normal of the production plane. In terms of the differential cross sections, \mathcal{P} is given by [28]

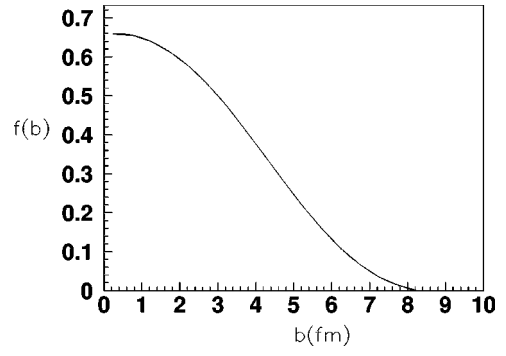


FIG. 3. The fraction $f(b)$ of Λ^0 's produced in the QGP to those produced by recombination as a function of impact parameter b .

$$\mathcal{P} = \left[\frac{d^2 \sigma_{\Lambda^0 \uparrow}}{d^2 b} - \frac{d^2 \sigma_{\Lambda^0 \downarrow}}{d^2 b} \right] / \left[\frac{d^2 \sigma_{\Lambda^0 \uparrow}}{d^2 b} + \frac{d^2 \sigma_{\Lambda^0 \downarrow}}{d^2 b} \right], \quad (33)$$

where $d^2 \sigma_{\Lambda^0 \uparrow}/d^2 b$ and $d^2 \sigma_{\Lambda^0 \downarrow}/d^2 b$ are the spin up and spin down (with respect to the normal of the production plane) differential cross sections, respectively. In the scenario where Λ^0 's originate from two different processes, one must take into account the corresponding contribution to the polarization.

As we have argued, Λ^0 's coming from the QGP regions are expected to be produced with their spins isotropically oriented and thus these do not contribute to the net Λ^0 polarization. We define

$$f(b) = \left[\frac{d^2 \sigma_{\Lambda^0}^{\text{QGP}}}{d^2 b} \right] / \left[\frac{d^2 \sigma_{\Lambda^0}^{\text{REC}}}{d^2 b} \right] \quad (34)$$

as the ratio of the differential cross sections for Λ^0 production from the QGP and from recombination processes. Figure 3 shows $f(b)$ as a function of the impact parameter b , for the case of Pb-Pb collisions, where $d^2 \sigma_{\Lambda^0}^{\text{REC}}/d^2 b$ and $d^2 \sigma_{\Lambda^0}^{\text{QGP}}/d^2 b$ are given by Eqs. (26) and (32), respectively.

Equation (33) can be written in terms of $f(b)$ as

$$\mathcal{P} = \frac{\mathcal{P}^{\text{REC}}}{[1 + f(b)]}, \quad (35)$$

where

$$\mathcal{P}^{\text{REC}} = \left[\frac{d^2 \sigma_{\Lambda^0 \uparrow}^{\text{REC}}}{d^2 b} - \frac{d^2 \sigma_{\Lambda^0 \downarrow}^{\text{REC}}}{d^2 b} \right] / \left[\frac{d^2 \sigma_{\Lambda^0 \uparrow}^{\text{REC}}}{d^2 b} + \frac{d^2 \sigma_{\Lambda^0 \downarrow}^{\text{REC}}}{d^2 b} \right], \quad (36)$$

given in the DMM by Eq. (2), is the Λ^0 polarization that would be observed in the absence of Λ^0 's produced by a QGP. Figure 4 shows the polarization obtained from Eqs. (2) and (35). Figure 4(a) shows the polarization as a function of p_T for different values of b . Figure 4(b) shows the polarization as a function of b for different values of p_T .

To incorporate the effects of the shift in momentum experienced by Λ^0 's traveling in the nuclear medium for densities below the critical density for QGP formation, we recall that, according to the analysis in Sec. III, a Λ^0 produced within a

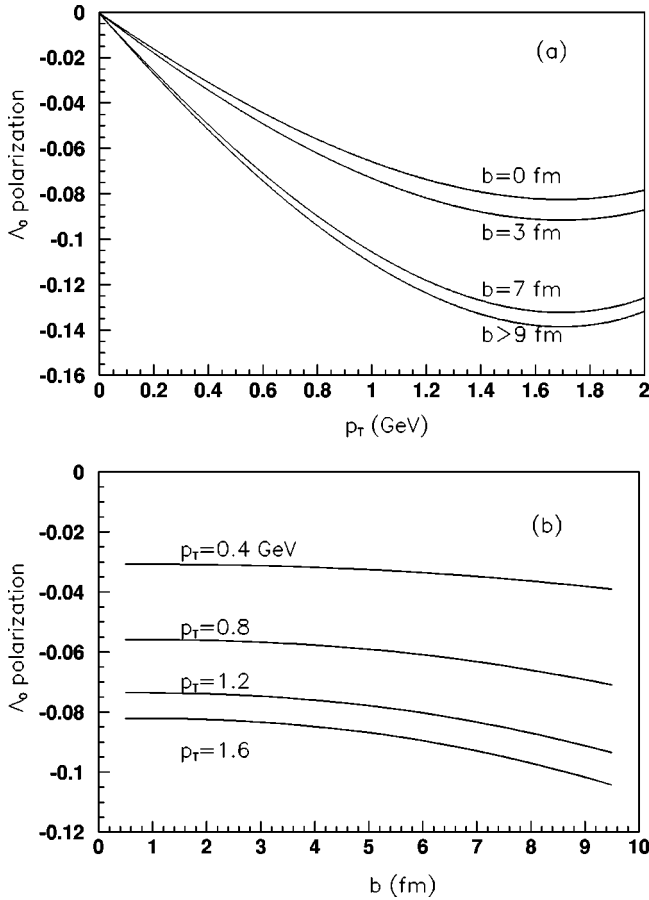


FIG. 4. Λ^0 polarization by recombination (a) as a function of p_T for different values of impact parameter b and (b) as a function of b for different values of p_T .

given phase space cell labeled by the pair of values (x, p_T) , is scattered into a different phase space cell, which, on average, is labeled by the pair of values $(\langle x \rangle, \langle p_T \rangle)$. Omitting from the analysis the spin-flip depolarization effects, the original Λ^0 polarization computed from Eq. (2) is preserved but corresponds (on average) to a detected Λ^0 with momenta labels $(\langle x \rangle, \langle p_T \rangle)$. This is shown in Fig. 5 where, for the purposes of comparison, we plot the polarization with and without considering the shift in transverse momenta due to multiple scattering, computed with the explicit values of $I = 0.2$ and $\Gamma = 0.01$ for two different values of the impact parameter b .

V. CONCLUSIONS

In conclusion, we propose to study the change in polarization of Λ^0 's, with respect to proton-proton reactions, as a means to identify the production of deconfined matter in ultrarelativistic nucleus-nucleus collisions. We have studied a model where Λ^0 's are produced by two competing mechanisms, namely, recombination type of processes, below the critical density for QGP formation, where we expect that Λ^0 's are produced polarized, and coalescence type of pro-

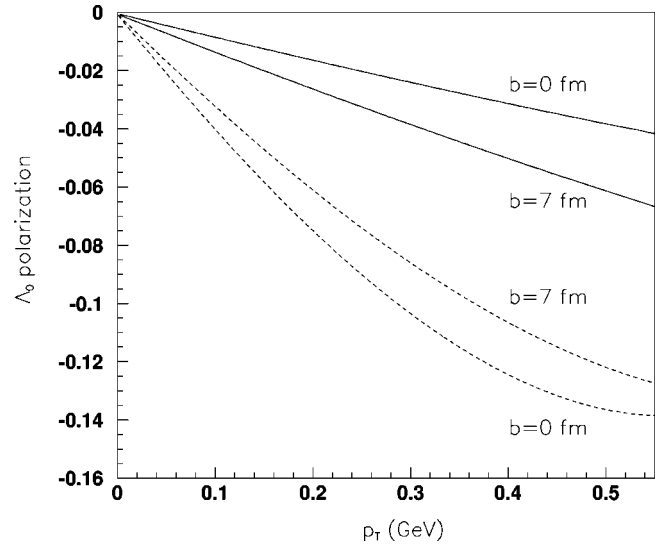


FIG. 5. Comparison of Λ^0 polarization values with (lower curves) and without (upper curves) the transverse momentum shift due to multiple scattering in the nuclear medium below the critical density for QGP formation.

cesses, above the critical density for QGP formation, where we expect that Λ^0 's are unpolarized. The overall polarization detected would thus depend on the relative contribution of each process to the overall Λ^0 yield.

To describe the polarization of Λ^0 's produced by recombination, we use the DMM, accounting for the effects introduced by multiple elastic scattering experienced by the produced Λ^0 's in the nuclear environment. Multiple scattering is responsible for two distinct effects: a momentum shift where the polarization of the produced Λ^0 's is preserved but their final momenta change and a depolarization due to spin flip interactions.

We have used the existing data on Λ^0 -nucleon interactions to obtain the inelasticity parameter I and have estimated the average dispersion angle per collision Γ . We have also given an explicit expression for the depolarization coefficient, in terms of the parameters describing the two-body Λ^0 -nucleon potential. These last parameters have yet to be measured at high energies.

Though our analysis is as quantitative as the existing data allow it, there is no doubt that in order for the model to have a stronger predictive power, more accurate data on Λ^0 -nucleon interactions at high energies are needed, which, together with an increasing interest on finding new probes for the existence of a QGP, can make Λ^0 polarization measurements a powerful analyzing tool in high energy heavy-ion collisions.

ACKNOWLEDGMENTS

Support for this work was received in part by CONACyT under ICM Grant No. 35792-E and by DGAPA-UNAM under Grant No. IN108001.

- [1] For a recent review on the subject, see U. W. Heinz, in *Hunting Down the Quark Gluon Plasma in Relativistic Heavy-Ion Collisions*, Proceedings of the Conference on Strong and Electroweak Matter (SEWM 98), Copenhagen, Denmark, edited by J. Ambjorn, P. Damaard, K. Kainulainen, and K. Rummukainen (World Scientific, Singapore, 1999), p. 81.
- [2] N. Angert *et al.*, in *Proceedings of the Conference on Quark Matter Formation and Heavy Ion Collisions*, edited by M. Jacob and H. Satz (World Scientific, Singapore, 1982), p. 557.
- [3] A.D. Panagiotou, Phys. Rev. C **33**, 1999 (1986); Int. J. Mod. Phys. A **5**, 1197 (1990).
- [4] B.E. Bonner *et al.*, Phys. Rev. D **38**, 729 (1988).
- [5] T.A. DeGrand and H.I. Miettinen, Phys. Rev. D **23**, 1227 (1981); **24**, 2419 (1981); T. Fujita and T. Matsuyama, *ibid.* **38**, 401 (1988); T.A. DeGrand, *ibid.* **38**, 403 (1988).
- [6] Y. Kitsukawa and K. Kubo, Prog. Theor. Phys. **103**, 1173 (2000).
- [7] R.C. Hwa, Phys. Rev. Lett. **52**, 492 (1984).
- [8] L.P. Csernai and J.I. Kapusta, Phys. Rev. D **29**, 2664 (1985); **31**, 2795 (1985).
- [9] M. Pepin *et al.*, Phys. Lett. **26B**, 35 (1967).
- [10] P. Aahlin *et al.*, Lett. Nuovo Cimento **21**, 236 (1978).
- [11] G. Bunce *et al.*, Phys. Rev. Lett. **36**, 1113 (1976).
- [12] G. Herrera, J. Magnin, L.M. Montaño, and F.R.A. Simão, Phys. Lett. B **382**, 201 (1996).
- [13] See *Total Cross Sections for Reactions of High Energy Particles* (Landolt-Börnstein), New Series Vol. I/12 a and I/12 b, edited by H. Schopper (Springer, Berlin, 1988).
- [14] J. Hüfner and A. Klar, Phys. Lett. **145B**, 167 (1984).
- [15] J.M. Hauptman, J.A. Kadyk, and G.H. Trilling, Nucl. Phys. **B125**, 29 (1977).
- [16] B. J. Uscinski, *The Elements of Wave Propagation in Random Media* (McGraw-Hill, New York, 1977).
- [17] J.A. Kadyk, G. Alexander, J.H. Chan, P. Gaposchkin, and G.H. Trilling, Nucl. Phys. **B27**, 13 (1971).
- [18] S. Ajimura *et al.*, Phys. Rev. Lett. **68**, 2137 (1992).
- [19] H.E. Conzett, Phys. Rev. C **48**, 924 (1993).
- [20] J. Bystricky, F. Lehar, and P. Winternitz, J. Phys. (Paris) **39**, 1 (1978).
- [21] D.J. Millener, A. Gal, C.B. Dover, and R.H. Dalitz, Phys. Rev. C **31**, 499 (1985).
- [22] M. May *et al.*, Phys. Rev. Lett. **47**, 1106 (1981); M. May *et al.*, *ibid.* **78**, 4343 (1997); K. Tanida *et al.*, Nucl. Phys. **A684**, 560c (2001).
- [23] J. Rafelski and B. Müller, Phys. Rev. Lett. **48**, 1066 (1982); **56**, 2334 (1986); T. Biró and J. Zimányi, Phys. Lett. **113B**, 6 (1982); Nucl. Phys. **A395**, 525 (1983).
- [24] G. Herrera and L.M. Montaño, Phys. Lett. B **381**, 337 (1996); G. Herrera, Rev. Mex. Fis. **43-S1**, 29 (1997).
- [25] J. Ranft, Act. Phys. Pol. B **10**, 911 (1979).
- [26] J.P. Blaizot and J.Y. Ollitrault, Phys. Rev. Lett. **77**, 1703 (1996).
- [27] J. Letessier, J. Rafelski, and A. Tounsi, Phys. Lett. B **389**, 586 (1996).
- [28] J.C. Anjos, G. Herrera, J. Magnin, and F.R.A. Simão, Phys. Rev. D **56**, 394 (1997).