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Possible evidence of disoriented chiral condensates from the anomaly in Ω and $\bar{\Omega}$ abundances at the super proton synchrotron

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Abstract. No conventional picture of nucleus–nucleus collisions has yet been able to explain the abundance of Ω and $\bar{\Omega}$ in central collisions between Pb nuclei at 158 A GeV at the CERN SPS. We argue that such a deviation from predictions of statistical thermal models and numerical simulations is the evidence that they are produced as topological defects in the form of skyrmions arising from the formation of disoriented chiral condensates. The estimated domain size falls in the right range to be consistent with the so far non-observation of disoriented chiral condensate (DCC) from the distribution of neutral pions.

Keywords. Hyperon production; disoriented chiral condensates; heavy-ion collisions; skyrmions.

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1. Introduction

Ever since their introduction [1–3], disoriented chiral condensates (DCC) have been the subject of intense theoretical efforts and the goal of experimental search. No sign of their formation has so far been found. One might be tempted to jump to the conclusion that DCC did not form in any of the heavy-ion collision experiments conducted to date. However, this is not the only conclusion that can be drawn from these experiments. DCC were supposed to manifest themselves in the distribution of neutral to total pion ratio only if a number of large domains with different chiral orientation were formed in the collisions. If the domains are small then it is impossible to tell, at least not via the pion ratio, whether DCC have been formed. We shall argue that it is possible to observe DCC via strange hyperons and that experimental data already provided some clues.

Our motivation originated from the data of Ω and $\bar{\Omega}$ yields at the super proton synchrotron (SPS). The measure of how well statistical models fit to particle ratios, χ^2, reduces by an order of magnitude if Ω and $\bar{\Omega}$ are left out [4]. The slope of the hadron m_{T} spectra follows a linear increase with mass, but Ω and $\bar{\Omega}$ deviate significantly from this [5,6]. This seems to be an indication that the triply strange hyperons do not follow the same trend of the other hadrons. It has been difficult for numerical models to generate the same yield of the strange hyperons at the SPS without re-adjusting parameters [7]. In general, there tend to be more hyperons than expected. One might wonder if the excess over the expected yield comes from all values of $k_{\rm T}$ or if this has an origin in only a particular range. Such information might provide further clues to the source of the additional hyperons. It has been shown that the triply strange hyperon yield is systematically higher than expected from model chemical analysis only at low $k_{\rm T}$ [8] and so this points to a source of low momentum Ω and $\bar{\Omega}$. We wish to remind readers at this point that DCC is also a source of low-energy pions. If DCC can produce hyperons, then it is in their nature as condensates to yield only low energy ones. But how can DCC give rise to baryons?

2. Producing hyperons from DCC

While one might be accustomed to classical chiral fields giving rise to low energy pions from the numerous recent works on DCC, it has been pointed out much earlier in the 60s that chiral fields could produce baryons [9–11]. The essential connection is the Skyrme model which has the Lagrangian density

$$\mathscr{L}_S = \frac{f_\pi^2}{4}\,{\rm tr}(\partial_\mu U \partial^\mu U^\dagger) + \frac{1}{32g^2}\,{\rm tr}[U^\dagger\partial_\mu U, U^\dagger\partial_\nu U]^2, \tag{1}$$

where $U = \exp\{i\tau\cdot\phi/f_\pi\} = (\sigma + i\tau\cdot\pi)/f_\pi$. Here f_π is the pion decay constant and g is essentially the π–ρ–π coupling constant. The equation of motion of this Lagrangian permits solutions called skyrmions. Spherically symmetric solutions can be found in the form

$$U = U_S = \exp\{i\tau\cdot\hat{r}\,F(r)\} \tag{2}$$

which depends on one radial function $F(r)$. It is required that $F(r)$ satisfies the boundary conditions $F(r\to\infty)\to 0$ and $F(r=0) = N\pi$. N is an integer called the winding number and has been identified as the baryon number [9–11]. For larger values of N it is not clear if the solutions really describe nuclei, but for the case of $N=\pm 1$ it represents a baryon and antibaryon, respectively. Therefore, classical chiral fields can generate composite fermions. Unlike the case of pions, it is not automatic that the fields will generate baryons. A non-trivial field topology must be formed before baryons can be produced.

Since the potential of the Skyrme Lagrangian is too complicated to permit easy understanding of condensates formation, let us discuss instead the case of a very simple version of the linear sigma model

$$\mathscr{L} = \frac{1}{2}\partial_\mu\Phi^\alpha\partial^\mu\Phi_\alpha - \frac{\lambda}{4}(\Phi^\alpha\Phi_\alpha - v^2)^2, \tag{3}$$

where $\Phi_\alpha = (\sigma,\pi_1,\pi_2,\pi_3)$. The potential is totally symmetric with respect to the chiral fields. The vacuum of this theory is simply the surface of a four-dimensional sphere or S^3. In order to form non-trivial topology, there must be domain formation where the chiral condensates in the neighboring domains should have sufficiently different chiral orientations so that they cover S^3 and would not be able to evolve back to the origin. The probability per unit volume for this to happen in the linear sigma model has been worked out [12–15] in terms of the correlation length ξ to be $0.04\xi^{-3}$. Because numerically flavour $SU(2)\simeq SU(3)$ we can apply this result to the hyperons [16–18].

3. Ω and $\bar{\Omega}$ production from DCC at the SPS

To examine the possibility of skyrmion formation from DCC we have to look at several things. How many hyperons originate from DCC per central collision? What is the likely domain size? It must not be too large so that DCC would manifest themselves in the distribution of the pion ratio, contradicting observational evidence. Finally, any hyperons thus formed should not be easily destroyed via collisions.

At the SPS the WA97 collaboration is the only experiment with published data of the yield of Ω and $\bar{\Omega}$ [19]. They gave $\bar{\Omega}/\Omega = 0.383 \pm 0.081$ and $\Omega + \bar{\Omega} = 0.410 \pm 0.08$ in an interval of $\Delta y = 1$ centering around $y = 0$. Unfortunately, this is quite a narrow range. We would like the Ω data in a wider rapidity range and possibly in the whole of 4π. The NA49 collaboration measured also the hyperons except the Ω and $\bar{\Omega}$ [20,21]. Furthermore, their Ξ results have been extrapolated to 4π in [22] to be $\Xi^- = 7.5 \pm 1.0$ and $\Xi^- + \bar{\Xi}^+ = 8.2 \pm 1.1$. These latter results are useful for us because WA97 also measured Ξ in the same rapidity window as their Ω measurement. They are $\Xi^- = 1.50 \pm 0.10$ and $\bar{\Xi}^+ = 0.37 \pm 0.06$. The combination of these results allow us to extrapolate the Ω results to 4π as follows:

$$\left(\frac{\bar{\Omega}}{\Omega+\Omega}\right)_{\mathrm{WA97}} \left(\frac{\Omega+\bar{\Omega}}{\Xi^- + \bar{\Xi}^+}\right)_{\mathrm{WA97}} \left(\Xi^- + \bar{\Xi}^+\right)_{\mathrm{NA49}} = 0.498\,. \tag{4}$$

One can expect on average half an $\bar{\Omega}$ per central collision at the SPS.

Since $\bar{\Omega}$ are rather rare, let us assume all of them are from DCC and that there is an equal chance of forming any of the octet or decouplet baryons. (One might expect that strange baryons with the more massive strange quark content should have a smaller probability. However, such flavour symmetry breaking would allow skyrmions to form in a smaller spatial region. This leads to larger probability per unit volume, thus compensating for the reduction in probability due to the larger mass [12,15].) This gives about seven skyrmions or antiskyrmions per central collision on an average. With about 2000 hadrons produced at the SPS and a not too unreasonable assumption of DCC forming at a matter density of around ten times normal nuclear matter of 1.7 hadrons/fm^3, one can estimate from the probability per unit volume discussed in the previous section that the correlation length or DCC domain size is $\xi \sim 2$ fm. This is too small a size for observation via pions and is consistent with theoretical expectation based on the system evolving in time in thermal equilibrium [23] or a slow time evolution of the effective potential back to the vacuum form in the annealing scenario [24]. These scenarios gave $\xi \sim 1.5$ fm and 3–4 fm, respectively. Note that the chance for observing DCC through this mechanism of forming hyperons is completely orthogonal to that of forming low-energy pions. The latter requires large domains whereas the former needs small ones.

Now we have to try to answer the question of whether hyperons coming from DCC can be easily destroyed or not. If they cannot survive the onslaught of the hadronic medium, any signal of DCC would be washed out. To check this we write down the rate for destroying Ω or $\bar{\Omega}$ via the most numerous and energetic of hadrons, namely π and K,

$$\frac{\partial \rho_\Omega}{\mathrm{d}t} = -\langle \sigma_{K+\Xi\to\pi+\Omega} v_{\pi\Omega}\rangle R_5 \rho_\pi^\infty \rho_\Omega - \langle \sigma_{\pi+\Xi\to K+\Omega} v_{K\Omega}\rangle R_1 \rho_K^\infty \rho_\Omega\,. \tag{5}$$

The notations are the same as those in [25]. This assumes thermal equilibrium of everything else except Ω and universal interaction matrix elements so that the difference due to flavours are completely in the phase space. Using results contained in [25] one can work out the destruction time-scales. For example at $T = 200$ MeV, the time-scale for changing Ω into something else by collision with pions is $\tau_\pi \sim 257$ fm and that by K is $\tau_K \sim 152$ fm. These are rather long times. One can conclude that there is a very good chance that hyperons from DCC can show up in the detectors.

In conclusion, we have shown that DCC formation can explain any excess or deviation from expectation of hyperons and antihyperons yields based on statistical models. Of course there is more than one way to do this kind of fits; see, for example [26]. They may or may not accommodate our interpretation presented here. However, both the theory and the phenomenology based on measured data seem to be self-consistent. For further details one can consult [15].

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