Is Anomalous Production of Ω and $\overline{\Omega}$ Evidence for Disoriented Chiral Condensates?

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No conventional picture of nucleus-nucleus collisions has yet been able to explain the abundance of Ω and $\overline{\Omega}$ hadrons in central collisions between Pb nuclei at 158*A* GeV at the CERN SPS. We argue that this is evidence that they are produced as topological defects arising from the formation of disoriented chiral condensates with an average domain size of about 2 fm.

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One of the most interesting observations in the field of high energy heavy ion physics is that the hadronic phase space is populated statistically (for the most recent analyses, see [1,2]). This means that the relative abundances of a wide variety of hadrons, such as protons, singly and doubly strange hyperons, pions, kaons, eta-mesons, and the antiparticles of these can all be described quite well in terms of a common temperature and chemical potentials (for electric charge, baryon number, and net strangeness). The time at which this occurs is referred to as chemical freeze-out. For central Pb + Pb collisions at a beam energy of 158*A* GeV at the CERN Super Proton Synchrotron (SPS), for example, analyses typically give this temperature in the range 175 ± 10 MeV. How this population is achieved dynamically is still a matter of much debate. There are proponents for hadronization from an earlier state of quark-gluon plasma, and there are proponents for strong interactions among the hadronic degrees of freedom alone without recourse to partonic ones [3]. However, the abundances of the Ω and $\overline{\Omega}$, which contain three strange quarks or antiquarks, are an anomaly. The purpose of this Letter is to put forward the argument that this anomaly is most easily understood if a disoriented chiral condensate (DCC) is formed. Formation of DCC is expected on quite general grounds [4–7], but up to now there has been no experimental evidence for it.

The anomaly is manifest in several ways. First, one obtains a chi-squared fit to the particle ratios which is much better if the Ω and $\overline{\Omega}$ are left out of the fitting procedure [8]. This results in a lower chemical freeze-out temperature of 145 ± 5 MeV and a prediction for the Ω and $\overline{\Omega}$ abundancies which are smaller than observations by a factor of 2. Second, an analysis of chemical equilibration times based on experimentally measured hadronic reactions indicates that the more strange valence quarks a hadron contains the longer it takes to establish chemical equilibrium [9]. Pions and kaons easily equilibrate. Even the time to equilibrate the antiproton is short enough, about 3 fm$/c$, to realize in a heavy ion collision on account of the many-body reaction $5\pi \rightarrow p + \overline{p}$ [9,10]. The equilibration times for the Ω and $\overline{\Omega}$ are longest of all, being on the order of several hundred fm$/c$ compared to the canonical nucleus-nucleus collision time of 10 fm$/c$ [3]. This is the result of numerically solving a coupled set of rate equations for hadrons. The reason it is so long is that the Ω (or $\overline{\Omega}$) may be produced via a sequence of two-body reactions like $K + N \rightarrow \Lambda + \pi$, $K + \Lambda \rightarrow \Xi + \pi$, $K + \Xi \rightarrow \Omega + \pi$, etc. and since the Ω is at the end of the chain it takes the longest to build up its abundance. Multibody reactions like $3K + 2\pi \rightarrow \Omega + \overline{\Omega}$ help and indeed were included in the rate equations, but these are slow compared to the buildup of antiprotons because the number of kaons is smaller than pions by about a factor of 5. Third, the microscopic transport model UrQMD [11], which is generally regarded to be the most sophisticated such model available, cannot reproduce the high yields of hyperons, especially the Ω and $\overline{\Omega}$. For those it falls short by about a factor of 2 to 3 for central Pb + Pb collisions at the SPS [12]. One way to account for the increased hyperon production within UrQMD is to lower the constituent quark masses to the values of the current quarks. Another is to increase the string tension by a factor of 3. The authors admit that both approaches are rather *ad hoc* and go on to say that the high yield of hyperons "is so far the only clear signal which contradicts transport calculations based on hadronic and string degrees of freedom." This may be true insofar as only two-body initial states are treated by UrQMD whereas detailed balance would require the inclusion of all time-reversed reactions [13], as in the case of the antiproton mentioned above.

We now propose that this anomaly arises from the formation of topological defects in DCC. These topological defects are identified with Skyrmions [14]. Such a mechanism for the production of baryons and antibaryons in heavy ion collisions was developed in a series of papers [15–18] but never applied quantitatively to data. The basic idea is that the chiral field (identified with pions if two flavors and with pions and kaons if three flavors) may become completely disoriented in coordinate space beyond a characteristic distance ξ, the correlation length or domain size. This disorientation may occur in a heavy ion collision if the entropy is very large, as one might easily imagine in such a violent event. It may also occur in jet fragmentation in pp, $p\overline{p}$, or e^+e^- collisions [19]. Simply put, a Skyrmion is a configuration where the chiral field winds nontrivially around the manifold of degenerate minima of the effective potential. Detailed calculations show that the probability per unit volume to form a baryon or antibaryon topologically is given by the following simple formula [18,20]:

$$\mathcal{P} \approx 0.08\xi^{-3}. \tag{1}$$

The interesting aspect of this mechanism is that it produces baryons and antibaryons above and beyond those formed by the recombination of quarks and antiquarks during a phase transition or jet fragmentation, even when the conversion of gluons into quark-antiquark pairs is taken into account to conserve (or create) entropy [16]. This mechanism is independent of whether or not a partonic gas, or quark-gluon plasma, preceded it.

Let us now review the experimental situation. The Ω and $\overline{\Omega}$ were measured in heavy ion collisions only at the CERN SPS, never at the BNL Alternating Gradient Synchrotron. The WA97 Collaboration observed them in Pb + Pb collisions at a beam energy of 158A GeV within one unit of rapidity centered around the nucleus-nucleus cm frame [21]. The results are quoted as $\overline{\Omega}/\Omega = 0.383 \pm 0.081$ and $\Omega + \overline{\Omega} = 0.41 \pm 0.08$ per central collision. The number of other hyperons measured are $\Xi^- = 1.5 \pm 0.1$, $\overline{\Xi}^+ = 0.37 \pm 0.06$, $\Lambda = 13.7 \pm 0.9$, and $\overline{\Lambda} = 1.8 \pm 0.2$. The NA49 Collaboration measured a variety of hadrons over a much wider range of momentum space but not, unfortunately, the Ω or $\overline{\Omega}$ [22]. These data were extrapolated in [2] to all momentum space. The relevant numbers are $\overline{p} = 10 \pm 1.7$, $\overline{\Lambda}/\Lambda = 0.2 \pm 0.04$, $\Xi^- = 7.5 \pm 1.0$, and $\Xi^- + \overline{\Xi}^+ = 8.2 \pm 1.1$. These 4π integrated yields are consistent within experimental and extrapolational uncertainties with the WA97 results. To get an estimate of the total number of $\overline{\Omega}$ in a central collision we use the total multiplicity of doubly strange hyperons measured by NA49 to convert the relative yields from WA97.

$$\left(\frac{\overline{\Omega}}{\Omega + \overline{\Omega}}\right)_{\mathrm{WA97}} \cdot \left(\frac{\Omega + \overline{\Omega}}{\Xi^- + \overline{\Xi}^+}\right)_{\mathrm{WA97}} \cdot (\Xi^- + \overline{\Xi}^+)_{\mathrm{NA49}} = 0.50\,.$$

So on average one $\overline{\Omega}$ is produced for every two central Pb + Pb collisions. In absolute terms this is very small because the total net baryon number in the collision is 414.

The experimental data show that $\overline{p} > \overline{\Lambda} > \overline{\Xi}^+ > \overline{\Omega}$. We now make the extreme approximation that all $\overline{\Omega}$ are produced as topological defects. Since topological production creates baryons and antibaryons in equal numbers this means that about 38% of the Ω originate from this same mechanism. We make the further approximation that there is equal probability to make a topological defect with the quantum numbers of any member of the baryon octet or decuplet. This is a reasonable approximation because the topological process is not sensitive to the mass of the defect created, as already pointed out in [16]. We can phrase this another way. Giving the s quark a greater mass (110–130 MeV) than the u and d quarks (5–7 MeV) suggests that the SU(3) chiral field is less likely to point in the strange than the nonstrange direction. Therefore one might conclude that Ω production by the defect mechanism would be suppressed relative to nonstrange baryons. However, this tends to be compensated by the increased production probability of Skyrmions when the effective potential is tilted by a nonzero quark mass [18]. Given that the decuplet baryons have spin 3/2 versus spin 1/2 for the octet means that the total number of topological defects (Skyrmions plus anti-Skyrmions) created in a typical central Pb + Pb collision is about 14. This number is small compared to the total number of baryons and antibaryons. It also means that the fraction of Ξ^- or $\overline{\Xi}^+$ which were originally created via the topological mechanism is smaller than for the triply strange hyperons. The fraction of singly strange hyperons is even less, and for antiprotons the fraction is estimated to be $0.25/10 = 2.5\%$. Once created, the nonstrange baryons for sure, and the singly and doubly strange hyperons to a lesser degree, will still undergo some amount of chemical equilibration. However, as shown above and in more detail below, the Ω and $\overline{\Omega}$ will not. Therefore they are a direct signal of the topological production mechanism.

To verify the indestructibility of the Ω and $\overline{\Omega}$ following their formation, we assume that all other hadrons have reached kinetic and chemical equilibrium and calculate the annihilation rates for such processes as $\pi + \Omega \to K + \Xi$ and $K + \Omega \to \pi + \Xi$. Koch, Müller, and Rafelski [9] assembled experimental data and assumed universal invariant matrix elements to obtain the needed cross sections. From Fig. 5.2 of their paper we parametrized the thermally averaged product of cross section with relative velocity for the inverse reactions (valid for $T > 100$ as expressed in MeV).

$$\langle \sigma(K + \Xi \to \pi + \Omega) v_{K\Xi} \rangle = 0.22 \text{ mb} \cdot c\,, \tag{2}$$

$$\langle \sigma(\pi + \Xi \to K + \Omega) v_{\pi\Xi} \rangle = 1.7 \left(\frac{170}{T}\right) \times e^{-705/T} \text{ mb} \cdot c\,. \tag{3}$$

Using these in the set of master rate equations given in their Appendix A and using the nonrelativistic limit for the K, Ξ, Ω and the ultrarelativistic limit for the π (valid for $100 < T < 200$), we obtained the following $1/e$ chemical equilibration times:

$$\tau(\pi + \Omega \to K + \Xi) = 160 \left(\frac{170}{T}\right)^{3/2} e^{142.5/T} \text{ fm}/c\,, \tag{4}$$

$$\tau(K + \Omega \to \pi + \Xi) = 36 \left(\frac{170}{T}\right)^{2} e^{354/T} \text{ fm}/c\,. \tag{5}$$

At $T = 170$ MeV, for example, these times are 370 and 290 fm/c, respectively, far too long to annihilate any Ω

or $\overline{\Omega}$. As the temperature decreases these times grow exponentially.

The DCC domain size ξ can now be estimated by equating the total number of topological defects with the production probability per unit volume, Eq. (1), times the volume of the nuclear system at the time of formation of topological defects. The total number of hadrons, both mesons and baryons, produced in central lead collisions with rapidities within two units of midrapidity is about 2000, as measured by NA49 [23]. Assuming that defect production occurs at a particle density on the order of 10 times nuclear matter density, or 1.7 hadrons/fm^3, translates into a volume equivalent to a non-Lorentz contracted lead nucleus. This volume roughly corresponds to a collision time in the cm frame of about 6 to 7 fm/c after first nuclear contact. The result is $\xi = 2$ fm. Is this reasonable? Essentially every dynamical calculation of the average domain size yields a number in the range of 1.4 to 3 fm, including thermal evolution [7], quenching [24], annealing [25], and bubble nucleation [26]. Because of the uncertainties involved in the present inference of ξ it may be more accurate to say that it is consistent with any value within that range. Unfortunately such a small value is practically undetectable in any other observable, such as fluctuations in the ratio of neutral to charged pions and Bose-Einstein interferometry [27].

There is one other aspect to the Ω and $\overline{\Omega}$ anomaly we have not yet mentioned. The inverse slope, T_{eff}, of the transverse mass distribution of most hadrons, such as pions, kaons, nucleons, lambdas, and deuterons all fall on a straight line when plotted as a function of the mass m of the hadrons [22,28,29].

$$T_{\text{eff}} = 180 + 105m\,. \tag{6}$$

Here T_{eff} is in MeV and m is in GeV. The Ω and $\overline{\Omega}$ strongly deviate from this systematic behavior; they have an inverse slope of 251 ± 19 MeV. This is more than 5 standard deviations away from the systematics. (There is a small deviation for the Ξ^- and $\overline{\Xi}^+$, but it is much less pronounced and within 1 standard deviation of systematics.) The much smaller inverse slope is to be expected if they are produced with small velocities relative to the surrounding matter, as is the case with the formation of topological defects. It is difficult to make this more quantitative without doing a full simulation.

In conclusion, we have shown that the anomalies associated with the Ω and $\overline{\Omega}$ observed in high energy heavy ion collisions may be understood if those hyperons are produced predominantly as topological defects in DCC. We infer a domain size of about 2 fm. This is too small to affect any of the other observables so far proposed for DCC. This production mechanism may arise if a quark-gluon plasma had been formed earlier in the collision, but it is not a requirement. In fact, data obtained with lighter ions at the SPS display a similar anomaly in the Ω and $\overline{\Omega}$ yields. To make further theoretical progress it would seem desirable to have a microscopic transport model which allows for the possibility of DCC formation and the production of topological defects. Data from the newly commissioned Relativistic Heavy-Ion Collider at BNL is eagerly awaited.

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