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Parity Doubling from Thermodynamics of Experimental Hadron Spectrum

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Abstract

Parity doubling is a way of recovering chiral symmetry, and one gets this behaviour in the real world of heavy ion collisions at mid-rapidity. Both the odd and even parity baryons show a tendency to be degenerate at a mass $3\pi T$ at the freeze-out temperature of about 140-160 MeV. We also show that strange baryons, the Λ and Σ, are above the value $3\pi T$ by about 100 MeV.

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It is well known that the QCD Lagrangian is chirally invariant in the light quark sector, apart from small quark masses. If one neglects these small masses of the light quarks, then one expects parity partners for every particle. For completeness let us recall the arguments given for example in T. D. Lee[1] about parity doubling using simple quantum mechanics. If a state, for example, the proton $|p\rangle$, is the eigenstate of a strong Hamiltonian H_{st}

$$H_{st}|p\rangle = m_p|p\rangle, \tag{1}$$

which has zero mass (u, d) quarks only, then there is chiral symmetry. This means the odd-parity axial charge Q_a^I (I the isospin) is conserved:

$$[Q_a^I, H_{st}] = 0, \quad I = 1,2,3,\ldots \tag{2}$$

and

$$H_{st}(Q_a^I|p\rangle) = m_p(Q_a^I|p\rangle). \tag{3}$$

But $Q_a^I|p\rangle$ has parity opposite to $|p\rangle$ and this means we expect parity doubled states. But the proton is at 938 MeV and its odd parity excitation is at 1520 MeV. The way out is to say that chiral symmetry is broken at T = 0 by the introduction of a massless Goldstone-Nambu particle (the pion in the $m_u = m_d = 0$ limit) and the state $Q_a^I|p\rangle$ is a $|\pi p\rangle$ state. At finite T we expect chiral symmetry to be restored and therefore parity doubled states.

Recently it was observed, that with dynamical quarks, finite temperature lattice calculations yield masses for mesons which go like $2\pi T$ and baryons which go as $3\pi T$ [2] For the pion, lattice-mass goes from 2.4 T at T_c to 4 T at $1.5T_c$ as we read off from figure 1 of [3]. This shows that for the pion there is still a very strong binding. The lattice group MT_c [4] have compared their results for the screening mass with those of a free quark gas considering finite size effect in some detail. They find that instead of the value πT for temporal extent $N_t = 4$ they find a value 2.634 T corresponding to a shift of 16%. For $N_t = 8$ they have a smaller shift of 4.8 %.

In a previous paper we have shown [5] that using the experimental energy states for π, ρ and the nucleon - Δ one can reproduce the lattice behaviour at quite low T, of order 140 MeV, which is believed to be reached in heavy ion collisions in CERN SPS and Brookhaven

AGS colliders. To be explicit, Stachel [6] has argued strongly in favour of a model of heavy ion collisions which suggests a hadron gas in chemical and thermal equilibrium with $T = 140 \pm 20 MeV$ confined in a volume of about $2400-2700\ fm^3$ in the mid-rapidity region, where the baryon density is low, $0.045/fm^3$. The support for this scenario comes from the absence of a peak at beam rapidity, the similarity of the data at CERN and Brookhaven at very different experimental conditions [1]. From a earlier paper by Brown, Stachel and Welke [8] where they use the experimental $N\Delta$ (nucleon-isobar) spectrum to estimate the Δ-s, From this percentage of the Δ-s they predict T.

We use a very similar model, only taking the positive parity and negative parity nucleons separately. The distributions are defined in terms of the chemical potential μ, as

$$f_i^{\pm} = 1/(\exp\frac{\epsilon_i - \mu}{T} \pm 1), \tag{4}$$

where the ± signs stand for fermions/bosons and the states are defined in terms of the hadron masses m_i:

$$\epsilon_i = \sqrt{m_i^2 + k^2} \tag{5}$$

with k is the momentum in GeV.

The number and energy in any particular state is then (for a volume V)

$$N_i = \frac{g_i V(r)}{2\pi^2} \int_0^{\infty} dk k^2 f_i^{\pm}, \tag{6}$$

$$E_i = \frac{g_i V(r)}{2\pi^2} \int_0^{\infty} dk k^2 \epsilon_i f_i^{\pm}, \tag{7}$$

and the thermal mass distribution for these particles are :

$$M(T) = \frac{\sum E_i}{\sum N_i} \tag{8}$$

We can define a transverse mass,

$$(m_i)_{\perp} = \sqrt{(m_i^2 + p_{\perp}^2)}, \tag{9}$$

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[1] a very telling picture is told by figure 2 of [6] when compared to fig. 17 of [7]

and define the transverse mass distribution as the ratio of

$$\frac{g_i V(r)}{(2\pi)^3} \int_{-\infty}^{\infty} dk_{||} \sqrt{((m_i)_{\perp}^2 + k_{||}^2)} f_i^{\pm}, \tag{10}$$

to

$$\frac{g_i V(r)}{(2\pi)^3} \int_{-\infty}^{\infty} dk_{||} f_i^{\pm}. \tag{11}$$

With this definition, we have checked that one can reproduce the transverse mass distribution (same as transverse momentum distribution for light particles like the pion). These show the well-known exponential behaviour, which has generated the idea of *characteristic temperature of emission* of different hadrons, T_H [6], [7]. While in the general the temperature is about 140 MeV, the heavier particles tend to show higher T_H, and the residual differences from 140 MeV may be due to side-flow [2].

We treat the nucleon-Δ even and odd parity states separately, using the 27 even and 29 odd states reported in [9]. Of these the last 4 even and 8 odd parity states are not in the summary table of [9] (II.24), we have taken them from VIII.58. We add these extra states since they have high degeneracy. The figure 1 shows that the masses of the even and odd state, defined with appropriate states in the above equation, tend to a common value, $3\pi T$. Thus we conclude that the experimental hadron spectrum supports the imaginary-time lattice calculations[3] and suggests that the mode of chiral symmetry restoration is parity doubling. In addition we find that this may be close to a T of the freeze-out T of 140 ± 20 MeV suggested by [6]. The doubling is not exact in the lattice presumably because of the small non-zero quark masses that are taken in their simulations. For the experimental states there are additional problems with convergence and may be additional experimental states would also help the merging. But again due to the finite current masses of the u and d quarks, one cannot expect exact parity doubling (in the same sense that the experimental pion mass at zero T is not zero but 139 MeV).

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[2] the authors are deeply indebted to Dr. Johanna Stachel for series of e-mails explaining this to them.

[3] Note that we are not directly comparing the lattice correlator masses, $M_c(T)$ with the mass defined in eq(8) but only ratios of $M(T)$ with ratios $M_c(T)$, and looking for claim for a *physical* result, namely parity doubling, which should be independent of the scheme of calculation.

To investigate this point further, we then try to see how the masses of the strange baryons go with T. We take the 16 Λ and the 18 Σ states from experiment, [9], now not distinguishing between the even and odd states. We show our results in Fig. 2, where we plot masses in units of $3\pi T$. The masses move about 100 MeV or so above the line $3\pi T$ in Fig. 2.

The results for the baryons at high T are not sensitive on μ and wide variations in it do not change the graphs. The small T end of the figures 1 and 2 however do depend on μ, but are not important for us. For the fig. 1 the μ was chosen to be 1 GeV, and for the strange baryons 1.2 GeV. The freeze out density in the heavy ion experiments is low, a fraction of the nuclear matter density.

In summary, we find that the experimental hadrons states used in a non-interacting statistical model gives the expected appproximate parity doubling in the freeeze out region of present day heavy ion collisions. We also find that the strange quark mass induces a 100 MeV extra energy at this T, implying the current strange quark mass may be higher approximately by this amount.

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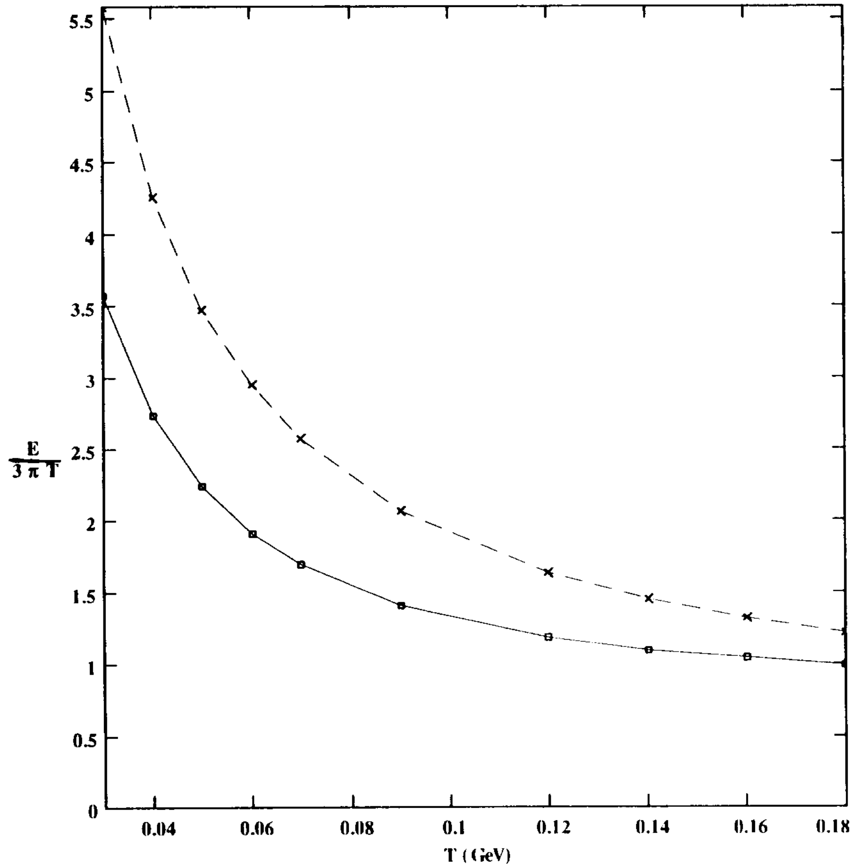
Figure Captions

Fig. 1 Nucleon even parity (solid line with boxes), Nucleon odd parity (dashed line with crosses) in units of $3\pi T$ versus temperature T, in units of GeV, using 21 even and 23 odd parity states from [9].

Fig. 2 Λ (solid line with boxes), Σ (dashed line with crosses) in units of $3\pi T$ (dot-dashed) versus temperature T, in units of GeV, using 16 Λ and 18 Σ states from [9].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5
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2
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E/3 π T
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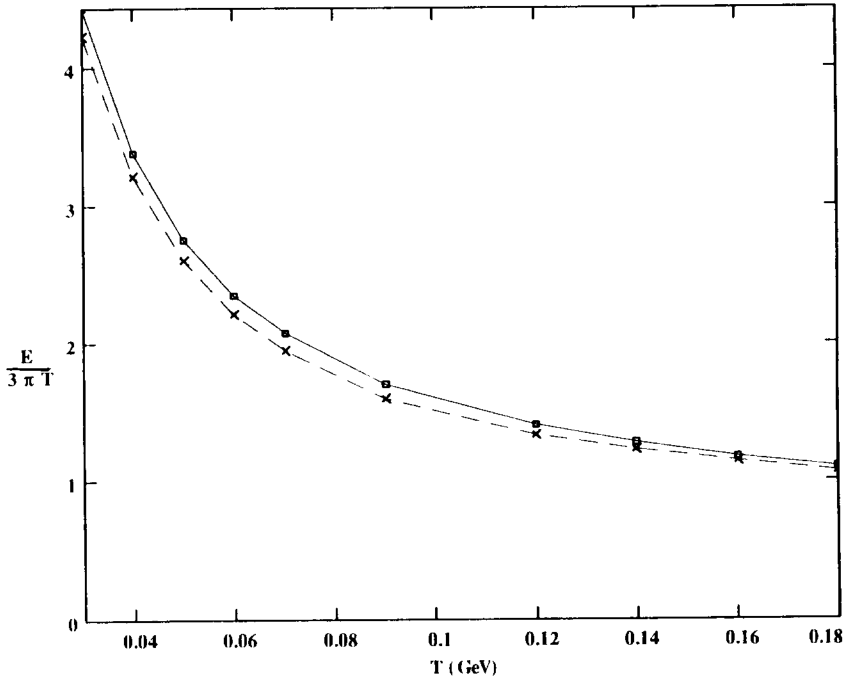
0.08
0.1
0.12
0.14
0.16
0.18
T (GeV)


4
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T (GeV)