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To the SPSLC Committee
CERN

Dear Colleagues,

We are writing to highlight an important physics opportunity for the CERN SPS. The QCD vacuum in which we live, which has the familiar hadrons as its excitations, is but one phase of QCD, and far from the simplest one at that. One way to better understand this phase and the nonperturbative dynamics of QCD more generally is to study other phases and the transitions between phases. Because of asymptotic freedom, the high temperature and high baryon density phases of QCD are more simply and more appropriately described in terms of quarks and gluons as degrees of freedom, rather than hadrons. The chiral symmetry breaking condensate which characterizes the vacuum phase melts away. The experimental heavy ion physics program can explore and map the QCD phase diagram as a function of temperature T and baryon number chemical potential μ. Recent theoretical developments suggest that a key qualitative feature, namely a critical point which in a sense defines the landscape to be mapped, may be within reach of discovery and analysis by the SPS, if data is taken at several different energies. The discovery of the critical point would in a stroke transform the map of the QCD phase diagram which we sketch below from one based only on reasonable inference from universality, lattice gauge theory and models into one with a solid experimental basis.

Arguments based on universality, supported by results from lattice gauge theory, indicate that the phase transition at zero net baryon density ($\mu = 0$) as a function of T between hadronic matter with broken chiral symmetry and quark-gluon plasma with chiral symmetry approximately restored is a smooth crossover in QCD with two light quarks, but no strange quark. If the two light quarks were massless, this crossover would be a second order phase transition. Instead, because of the explicit chiral symmetry breaking introduced by the light quark masses, physics changes dramatically but smoothly in the crossover region, and no correlation lengths diverge. Arguments based on a variety of models indicate that the transition as a function of T is first order at large μ. (This statement is strengthened by recent developments in our understanding of color superconductivity in cold dense quark matter, but does not rely on it.) This suggests that the phase diagram features a critical point E at which the line of first order phase transitions present for $\mu > \mu_E$ ends. At μ_E, the phase transition is second order and the correlation length in the σ channel diverges due to universal long wavelength fluctuations of the order parameter. This results in characteristic signatures, analogues of critical opalescence in the sense that they are unique to collisions which freeze out near the critical point, which can be used to discover E.

Returning to the $\mu = 0$ axis, universal arguments, again backed by lattice simulation, tell us that if the strange quark were as light as the up and down quarks, the transition would be first order, rather than a smooth crossover. One of us (FW) noted several years ago that this means that if one could dial the strange quark mass m_s, one could find a critical m_s^c at which the transition as a function of temperature was second order. The value of m_s^c is an open question, but lattice simulation suggests that it is about half the physical strange quark mass. This means that the phase transition at low μ (as achieved in the big bang or in sufficiently energetic heavy ion collsions) is a smooth crossover.

These observations fit together in a simple and elegant fashion. If we could vary m_s, what we would find is that as m_s is reduced from infinity to m_s^c, the critical point E in the (T, μ) plane moves toward the $\mu = 0$ axis. In nature, E is at some nonzero T_E and μ_E. When m_s is reduced to m_s^c, μ_E reaches zero. Of course, experimentalists cannot vary m_s. They can, however, vary μ. The AGS, with beam energy 11 AGeV, corresponding to $\sqrt{s} = 5$ GeV, creates fireballs which freeze out near $\mu \sim 500 - 600$ MeV. When the SPS runs with $\sqrt{s} = 17$ GeV (beam energy 158 AGeV), it creates fireballs which freeze out near $\mu \sim 200$ MeV. By dialing $\sqrt{s}$ and thus μ, experimenters can find the critical point E.

The map of the QCD phase diagram which we have sketched is simple, coherent and consistent with all we know theoretically; the discovery of the critical point would provide an experimental foundation for the central qualitative feature of the landscape. This discovery would in addition confirm that in higher energy heavy ion collisions and in the big bang, the QCD phase transition is a smooth crossover. Furthermore, the discovery of collisions which create matter that freezes out near E would imply that conditions above the transition existed prior to freezeout, and would thus make it much easier to interpret the results of other experiments which seek signatures which probe the partonic matter created early in the collision.

We as theorists must clearly do as much as we can to tell experimentalists *where* and *how* to find E. The "where" question, namely the question of predicting the value of μ_E and thus suggesting the $\sqrt{s}$ to use to find E, is much harder for us to answer. One of the things which is intrinsic to the picture we have described is that μ_E is sensitive to the mass of the strange quark. Crude models suggest that μ_E could be $\sim 600 - 800$ MeV in the absence of the strange quark; this in turn suggests that in nature μ_E may have of order half this value, and may therefore be accessible at the SPS if the SPS runs with $\sqrt{s} < 17$ GeV. However, at present theorists can not predict the value of μ_E even to within a factor of two.

The other half of the "where" question is the question of how close does one have to come to E in order to detect its presence. That is, how big steps in $\sqrt{s}$ can one safely take and still be reasonably confident of discovering E if it is there to be found? To answer this, we must estimate $\Delta\mu$, the width in μ of the region centered at μ_E within which the correlation length is longer than 2 fm, and thus detectable effects of E arise. Here again, only crude models are available. KR's analysis within one toy model (an NJL model) suggests that in the absence of the strange quark, $\Delta\mu \sim 120$ MeV for $\mu_E \sim 800$ MeV. MS has found similar results within a random matrix model. It is likely over-optimistic to estimate $\Delta\mu \sim 120$ MeV when the effects of the strange quark are included and μ_E itself is significantly reduced. A conservative estimate would be to use the models to estimate that $\Delta\mu/\mu_E \sim 15\%$ in an infinite system. Finite size effects must increase $\Delta\mu/\mu_E$. We therefore propose that a reasonable estimate, the best we can offer for use in planning experimental strategy, is $\Delta\mu/\mu_E \sim 20 - 30\%$. This suggests that if experiments could be done at about four energies between AGS energy ($\sqrt{s} = 5$) and maximum SPS energy ($\sqrt{s} = 17$ GeV), there would be a good chance of finding E if it lies within the range 200 MeV $< \mu_E <$ 600 MeV. An SPS run at $\sqrt{s} = 9$ GeV (beam energy 40 AGeV) is already planned. This data, together with that already taken at $\sqrt{s} = 17$ GeV, together with data from two (or perhaps only one) additional beam energies in between would allow the SPS to search for the critical point over a substantial range of parameter space. There is therefore a very strong scientific argument for an 80 AGeV run. If one additional run, say at 120 AGeV, were also possible it would be ideal.

It should be clear by now that although we are trying to be helpful with the "where" question, we are not very good at answering it quantitatively. This question can only be answered convincingly by an experimental discovery. What we as theorists *can* do reasonably well is to answer the "how" question, thus enabling experimenters to answer "where". This is the goal of a recent paper by three of us (hep-ph/9903292 by MS, KR, ES). The signatures we have proposed are based on the fact that E is a genuine thermodynamic singularity at which susceptibilities diverge and the order parameter fluctuates on long wavelengths. The resulting signatures are *nonmonotonic* as a function of $\sqrt{s}$: as this control parameter is varied, we should see the signatures strengthen and then weaken again as the critical point is approached and then passed.

The simplest observables we analyze are the event-by-event fluctuations of the mean transverse momentum of the charged particles in an event, p_T, and of the total charged multiplicity in an event, N. We calculate the magnitude of the effects of critical fluctuations on these and other observables, making predictions which, we hope, will allow experiments to find E. As a necessary prelude, we analyze the contribution of noncritical thermodynamic fluctuations. We use our analysis to argue that NA49 data (hep-ex/9904014) is consistent with the hypothesis that most of the event-by-event fluctuation observed in the data is thermodynamic in origin. This bodes well for the detectability of systematic changes in thermodynamic fluctuations near E.

As one example, consider the ratio of the width of the true event-by-event distribution of p_T to the width of the distribution in a sample of mixed events. We called this ratio $\sqrt{F}$. NA49 has measured $\sqrt{F} = 1.002 \pm 0.002$, which is consistent with expectations for noncritical thermodynamic fluctuations. We argue that critical fluctuations can increase $\sqrt{F}$ by $10 - 20\%$, fifty times the statistical error in the present measurement. There are other observables which are even more sensitive to critical effects. For example, a $\sqrt{F_{\rm soft}}$ defined using only the 10% softest pions in each event, may easily be affected at the factor of two level. We have estimated the magnitude of the effect of critical fluctuations on many other observables, including some like the mean multiplicity of soft pions which do not require event-by-event analysis.

NA49 data demonstrates very clearly that SPS collisions at $\sqrt{s} = 17$ GeV *do not* freeze out near the critical point. E has not yet been discovered. The nonmonotonic appearance and then disappearance (as $\sqrt{s}$ is varied) of any one of the signatures of the critical fluctuations we have described would be strong evidence for critical fluctuations. If nonmonotonic variation is seen in several of these observables, with the maxima in all signatures occurring at the same value of $\sqrt{s}$, this would turn strong evidence into an unambiguous discovery of the critical point. The quality of the present NA49 data, and the confidence with which we can use it to learn that collisions at $\sqrt{s} = 17$ GeV do not freeze out near the critical point make us confident that the program of experimentation which we have described can realistically be expected to teach us much about the phase diagram of QCD, and could result in a discovery of what is perhaps the most fundamental feature of the landscape. Once the critical point E is discovered, it will be prominent on the map of the phase diagram which will appear in any future textbook on QCD.

Sincerely,

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