September 20, 2004

CERN SPSC
Prof. John Dainton, Chairman
Prof. Jos Engelen, Chief Scientific Officer

Dear Colleagues,

We write to highlight an important physics opportunity for the CERN SPS. Heavy ion collision experiments at SPS can make a fundamental contribution to our understanding of the phase diagram of QCD by discovering the QCD critical point. Theoretical studies show that the critical point, where the first order phase transition separating quark-gluon plasma from hadronic gas comes to an end and the two phases become indistinguishable, is within the experimental reach of the SPS. The CERN SPS is the only accelerator in the world, which has all the capabilities in place right now to discover the critical point of QCD.

Asymptotic freedom of QCD dictates that at high enough temperatures, strongly interacting matter must behave as a plasma of the fundamental QCD constituents: quarks and gluons. The first goal of the heavy ion collision program is to confirm the theoretical expectation that hadronic matter, when brought to sufficiently high temperatures, does indeed behave as quark-gluon plasma. Due to experiments at the CERN SPS and RHIC, one has now accumulated a large body of experimental evidence that this is indeed the case.

How does the transition between the two states of QCD matter happen? What are the properties of matter near the transition point? Is there a first order transition, as in water at its boiling point at atmospheric pressure, or is there a smooth crossover, as for water/steam at higher pressures or for the ionization of gases? Theoretical studies indicate that the answer depends on the net density of baryons, or the baryon chemical potential μ_B. If μ_B is zero or small, first principles lattice calculations show a crossover. On the other hand, at sufficiently large μ_B models, as well as recent lattice studies, indicate that the transition becomes first order. The following picture emerges: as we decrease the chemical potential μ_B and follow the first order transition line, the transition weakens and then disappears, giving way to a crossover. The end-point of the first order phase transition is a second-order critical point, the one sharply defined point on the QCD phase diagram.

Where on the phase diagram of QCD is the critical point to be found? This question can be conclusively answered by CERN SPS heavy-ion collision experiments. The most recent lattice studies suggest that the critical point occurs at $\mu_B = 360$ MeV and $T = 160$ MeV. Theoretical uncertainties are, however, quite large, and many model calculations give predictions which scatter around on the $T - \mu_B$ plane. Experimental observation is crucial to establishing the existence and location of the critical point.

Given that nature seems to have chosen a continuous crossover at $\mu_B = 0$, the location of the QCD critical point in (μ_B, T) is the foremost example of a quantitative landmark on the phase diagram of nature that can be predicted from a fundamental theory and studied in real experiments. It is of course very important to measure the properties of the quark-gluon plasma, all of which will be continuously connected to those of a hadron gas even though they may differ grossly in their quantitative values. This quest is ongoing at RHIC, and heavy ion collisions at the LHC can be expected to play a leadership role here when they begin. However, locating the critical point on the phase diagram is equally important, as it provides a sharp answer to a precise question about how the phase diagram of QCD should be drawn in any future text book on the theory.

How can experiments locate the point without prior precise knowledge of its position? If it lies in the region which can be reached by varying the collision parameters, the energy and the ion size, the key is to vary these control parameters and see the signatures of freezeout near the critical point turn on and turn off. Increasing the collision energy leads to collisions which freeze out at smaller μ_B, and is thus the most important control parameter to vary if one wants to scan the phase diagram for the critical point. But, decreasing the size of the ions is also important as it makes freezeout occur at higher temperatures, closer to the phase boundary.

What observables signal that freezeout is occurring near the critical point? Event-by-event fluctuations offer robust signatures of the critical point, because every critical point is characterized by the divergence (or, in a system of finite extent and finite duration, significant increase) of the fluctuations. In a familiar example, the critical opalescence at the liquid-gas critical point is the result of critical fluctuations. If freezeout occurs close to the QCD critical point, fluctuation observables should show an increase, which should be contrasted to the baseline of fluctuations when the freezeout occurs in other points of the phase diagram. A non-monotonic behavior of all observables sensitive to the critical point fluctuations, as a function of energy and ion size, is a signature of the critical point.

Why is the CERN SPS in a unique position? RHIC is focussing its efforts on the highest energy collisions that it can achieve, which is natural in the quest to study the properties of the quark-gluon plasma. The LHC will extend this quest further. At these high collision energies, μ_B is small ($\approx$ 30 MeV at $\sqrt{s}$ = 200 AGeV at RHIC). In contrast, by doing collisions with $\sqrt{s}$ ranging from 6 AGeV to 17 AGeV, the SPS has already demonstrated that it can explore the regime 250 MeV $< \mu_B <$ 450 MeV. This is precisely the regime that the current, still imprecise, theoretical calculations suggest is worth exploring for signs of the critical point. In the long term, the CERN SPS will have competition at the higher end of this μ_B range from the planned new facility at GSI, and conceivably could have competition from fixed target experiments at RHIC, but for the present the SPS has an opportunity to make a unique impact.

We strongly encourage CERN SPS to undertake an experimental effort with the following components:

1. Light and medium ion energy scan.

The recent data from NA49 indicates that certain fluctuations observed in collisions with beam energy 158 GeV increase if the size of the ions is made smaller. A conceivable explanation of this effect is that the critical point temperature is above the freezeout temperature of the heaviest ions, and the higher freezeout temperature in smaller ion collisions is closer to the critical point. If this is the case, the signatures of the critical point should be more pronounced if the energy scan is performed with smaller ions.

2. Comprehensive event-by-event analysis of the collisions at various energies and ion sizes, focussing on low p_T.

It is at present not clear whether the observed fluctuations referred to in point 1. are related to the critical point. The crucial issues are whether they are dominated by fluctuations at low p_T, as must be the case if they are critical fluctuations, and whether they are accompanied by fluctuations of other low p_T-observables that must also be enhanced if freezeout really is occuring near the critical point. A crucial component of any future experimental effort, then, is to have the humanpower capabilities needed to do a comprehensive analysis of event-by-event fluctuations, and the detector capabilities needed to focus on the fluctuations occuring at, say, $p_T < 500$ MeV, thus filtering out irrelevant effects.

3. Continuing the Pb-Pb energy scan.

Data on Pb-Pb collisions at several collision energies is already available. Additional Pb-Pb runs at beam energies of 60 and 120 GeV would complete this energy scan. This might (or might not) be better motivated after first results from the program in points 1. and 2. are in hand. Any program should allow for such runs to be built into the plans at a later date, if motivated.

We support the Light-Ion program proposed by NA49 collaboration. This proposal contains major components of the program we advocate in this letter.

Sincerely yours,

Krishna Rajagopal (MIT) and Misha Stephanov (UIC)

cc: Marek Gazdzicki