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STATUS AND PROSPECT OF HIGH ENERGY HEAVY ION PHYSICS IN EUROPE

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Abstract

The Nuclear Physics European Collaboration Committee (NuPECC) intends to present shortly a Report on "The future of Nuclear Physics in Europe". To this end NuPECC has formed working groups to prepare reports on the different areas of Nuclear Physics; these were presented at the NuPECC Workshop at Ruthin Castle (U.K.), on 17-21 March, 1991.

This survey is based on the report of the Working Group on Quark-Gluon Plasma, and on numerous suggestions made by the community active in the field. It is presented by the members of the Working Group on QGP, but does not necessarily represent the view of NuPECC.

The physics motivations for ultrarelativistic heavy ion experiments are recalled and the predictions of equilibrium thermodynamics based on statistical QCD are discussed. We examine what we have learned from experiments, and what nuclear effects have been observed. Finally, a review of existing and planned facilities is given, together with an assessment of how adequate they are to answer questions about the formation and the properties of strongly interacting bulk matter, the quark-hadron phase transition and the quark-gluon plasma.

1. INTRODUCTION

The analysis of strongly interacting matter, based on QCD as the underlying dynamics, constitutes one of the fundamental challenges of present day physics. QCD predicts that at high density such matter should undergo a phase transition to an entirely new state, a plasma of deconfined quarks and gluons; the constituents of this new phase are the fundamental building blocks out of which all strongly interacting particles are made. An experimental test of the large scale features of QCD are therefore of basic importance.

In the high energy collision of two nuclei we expect abundant deposition of energy into a space-time region which is much larger and has longer lifetime than the fundamental hadronic scale of 1 fm. Such collisions thus provide us with an opportunity to study in laboratory hot and dense hadronic matter under conditions which existed in the early universe. Central goals of such investigations are (i) the determination of the properties of the strongly interacting matter at different densities, (ii) the determination of the nature and parameters of the quark-hadron phase transition which is predicted by lattice calculations and by phenomenological models, and (iii) the experimental verification of the existence of quark-gluon plasma. The investigation of the properties of strongly interacting matter at extreme densities provides a link between nuclear and particle physics. It is a natural extension of the study of properties of nuclear matter and it is much inspired by the dynamics of strong interactions as revealed in particle physics. In addition, the field is also of interest to astrophysics and cosmology.

A first exploratory phase in 1986-1987 at the CERN-SPS pursued successfully the aim to demonstrate the feasibility of an experimental study of dense hadronic matter. New results are expected from experiments in 1990-1993. In this stage, a class of detectors adapted from high energy experiments opened the way to dedicated apparatus and provided the basis for a collaboration between nuclear and particle physicists.

To achieve energy densities which are high enough for the deconfinement of quarks and gluons, nuclear beams with energies well above 100 GeV/nucleon are needed (for fixed target experiments). The European potential for this is quite good: at the CERN-SPS, lead beams will be available in 1994, upgrading the present program with Oxygen and Sulphur beams significantly. The CERN Large Hadron Collider (LHC), which is expected to start operation in 1998, will increase the c.m. collision energy by more than a factor of 100 and is expected to lead to energy densities several times higher than those at SPS energies. As discussed in more detail below, even with conservative estimates of the energy densities, the gain from the large collision energy at LHC may well be a decisive factor in the observation of deconfinement transition. On the other hand, the SPS provides the best energy range for the study of matter at high baryon density. The two CERN facilities thus nicely complement each other.

2. THEORETICAL BASIS

At extreme density, we expect deconfinement because the presence of many colour charges will screen the confining potential between the members of a given $q\bar{q}$ or qqq system. *In the early universe*, this transition presumably took place in the inverse direction some tens of microseconds after the big bang. *Heavy ion experiments* should provide the tool to study in the laboratory both the quark-hadron transition and the properties of the primordial quark-gluon plasma. On the *theoretical side*, strong interaction thermodynamics, including the critical behaviour at the transition, is described by statistical QCD.

2.1 Predictions of statistical QCD

The main transition parameters (energy density, temperature, baryon density, screening length) have been studied in statistical QCD, both by computer simulation of the lattice formulation and in various phenomenological approaches.

In the computer simulation of lattice QCD, one tries to calculate the relevant quantities from first principles, without any simplifying physical assumptions. The results give us a reasonably good general understanding of the critical behaviour of strongly interacting matter at vanishing baryon number density ($n_B = 0$), even though the quantitative reliability is at present still somewhat limited by technical restrictions (memory size, operating speed of available supercomputers). Nevertheless, it appears that this is the first time that basic dynamics leads directly to predictions for equilibrium thermodynamics.

The main predictions from lattice QCD are:

- there is an abrupt change from hadronic to QGP regime, which may be interpreted as a (weak) first order phase transition;

- deconfinement and chiral symmetry restoration occur at the same temperature T_c; for 2-3 light quark flavours one finds $T_c \approx$ 150-200 MeV, which corresponds to a critical energy density $\varepsilon_c \approx$ 1-3 GeV/fm^3, necessary to produce QGP;
- the plasma becomes ideal [$\varepsilon \approx 3P$, where P is the pressure] only for $T/T_c \approx$ 1.5-2.

Alternative approaches to lattice QCD are given by effective Lagrangian models, bag models and by chiral perturbation theory. Their results agree essentially with those from lattice QCD.

3. WHAT WE HAVE LEARNED

The basic questions we have to ask are these:

- Do nuclear collisions lead to systems dense enough, large enough, long-lived enough to be treated by thermodynamics based on QCD?
- Has the system produced in a nuclear ion collision reached thermal equilibrium?
- How can we test if the produced system was, in its early "primordial" history, in a deconfined state?

3.1 Collision and thermal features

The crucial features of the collision, such as the initial energy density, the temperature, or the entropy density cannot be measured directly but have to be inferred from experimental observables. The basic quantities for such estimates are the multiplicity density dN/dy of produced hadrons, the abundances of various particle species and their distribution in phase space (p,y).

The most significant experimental observations are summarized as follows.

Energy density

Large multiplicities, of the order of hundreds per unit of rapidity, have been measured. The multiplicity is strongly correlated to the transverse energy E_T. The shape of the transverse energy distribution is governed by the geometry of nucleus-nucleus collisions, reflecting the increasing number of "participants" with decreasing impact parameter b, which, through their collisions, build eventually the observed E_T. The corresponding values of *energy density* go up to $\varepsilon_A \approx 2$ *GeV/fm*^{3} at 200 GeV/nucleon with Oxygen and Sulphur beams at SPS. For central Pb-Pb collisions, the Bjorken approach ($\varepsilon_A \approx 0.1\, A^{1/3} \ln\sqrt{s}$) leads to the predicted average values of ε_A at SPS, RHIC and LHC shown in Table I.

Baryon density

Relatively high ($\geq 60\%$) stopping power has been observed. It was expected that increasing the momentum of the incident beam would increase the "transparency" of the colliding nuclei, so that the overall gain in energy density of the system would be only marginal. The "stopping power" of the colliding nuclei is defined as the ratio S of the measured transverse energy E_T to the maximum theoretical available transverse energy of the collision E_T^{max} (S= E_T/E_T^{max}). Far of central collisions, S was found to be close to 100% for beam energies between 14.5 and 60 GeV/nucleon, and going to 200 GeV/nucleon, it decreases only to about 70%; hence, nuclear transparency turned out to be not so important up to now. Owing to the large stopping power of nuclear matter, large baryon densities were observed even in Sulphur-Sulphur collisions at the SPS.

From p-A collisions at $A \approx 200$, we know that in passing through a nuclear target, the projectile proton loses approximately two units in rapidity. With this loss, the maximal stopping occurs for $\sqrt{s} \approx 7$ GeV. Model calculations suggest then that the *baryon density* so obtained becomes as large as $n_B/n_0 \approx 7.5$ at the point of maximum stopping. On the other hand, stopping in nucleus-nucleus collisions may well be higher, and many event generator studies give values up to $\delta y = 3.5$.

The *baryon number distribution* is centered at Y-δy, where Y denotes the maximum rapidity and δy is the rapidity loss. The overall baryon free region in rapidity thus becomes $(\Delta Y)_0 = 2Y - 4\delta y$. For the mentioned values $\delta y = 2$ and $\delta y = 3.5$, one gets the predicted baryon free regions shown in Table 1.

Table 1 - Predicted values for central Pb-Pb collisions

Machine *(c.m.s. energy) (GeV/n-n)*	ε_A *(GeV/fm³)*	**2Y**	$(\Delta Y)_0$	R_F *(fm)*
SPS (17)	1.7	5.8	0	17
RHIC (200)	3.1	10.7	0 - 2.7	25
LHC (6300)	5.2	17.6	3.6 - 9.6	31

Space-time evolution

Identical particle interferometry (Hanbury-Brown–Twiss) provides an excellent tool for the determination of many characteristics of the space-time evolution of the system formed in the collision. So far the experimental data at the SPS indicate that all size parameters are by a factor 2 larger than those predicted by free streaming models, indicating that collective effects are present. If freeze-out takes place when the mean free path λ of pions has reached the size of the system, the freeze-out radius becomes $R_F^\lambda \approx 0.7\ (dN/dy)^{1/2}$, in agreement with present SPS data. In the case of central lead-lead collisions one then gets the radii shown in Table I.

3.2 Signals of the primordial state

We can identify ways to test whether the system produced in a high energy heavy ion collision was, in its early "primordial" history, in a deconfined state or not.

One way is to look for signals which are produced at early times and are not affected by the subsequent hadronization. Possible observables of this type are *thermal dileptons* and *thermal photons,* which are emitted by the plasma and then escape. In the same context, one may also study the effect of the produced dense medium on the observed production of *heavy quark bound states* (J/Ψ suppression and its generalization) or *hard jets.*

Another approach is to look for primordial remnants in the observed hadron features. In this context, possible candidates are: *discontinuities in the momentum distribution* of the secondaries, reflecting a first order phase transition; *strangeness enhancement,* if significantly different for a hadron gas and a QGP; and *resonance modifications* (shifts in mass or width).

- **Thermal dileptons**

  Thermal dileptons are produced when $\pi^+\pi^-$ or $q\bar{q}$ pairs annihilate in a hot pion or quark gas, respectively. But dileptons are produced as well in the decay of low mass vector mesons ρ, ω and φ, and in hard interactions between incident partons at a very early stage of the collision, leading to Drell-Yan pairs or to the production of heavy ($c\bar{c}$ or $b\bar{b}$) vector mesons, which subsequently decay into lepton pairs. The main competition for thermal dileptons at high mass comes from Drell-Yan production. However, thermal dileptons and Drell-Yan pairs have different functional dependences on the dilepton pair mass M, and so should be distinguishable. For sufficiently high energy density there seems to be a a clear-cut window for high mass dileptons, between resonance decays and Drell-Yan production. The detection of low mass thermal dileptons, from $\pi^+\pi^-$ annihilation in a pion gas or from $q\bar{q}$ annihilation in a quark gas, is not so easy, since large backgrounds from π° and η Dalitz decays and from virtual Bremsstrhalung must be subtracted.

- **Thermal photons**

  For thermal photons, the main background at low momenta comes from the decay of hadrons, mainly π° and η; of high momenta, there are in addition direct photons from Compton scattering. The observation depends very much on how well the hadron decays can be identified and eliminated.

From the experimental point of view, as far as thermal dileptons and thermal photons are concerned, no clear signal has been so far seen within experimental sensitivities.

- **Heavy quark bound states**

Studying the spectra of *heavy quark bound states* can be a more promising tool of analysis. A suppression of the J/Ψ signal relative to the Drell-Yan continuum had in fact been predicted as a signature for deconfinement, based on Debye screening between color charges. However, this effect has to be distinguished from conventional absorption in dense hadronic matter with initial state parton scattering.

Strong J/Ψ suppression with a pronounced P_T dependence has been measured. The production rate of J/Ψ relative to the dimuon continuum drops significantly with increasing E_T (up to 50%) in Oxygen-Uranium and Sulphur-Uranium collisions at 200 GeV/nucleon. This suppression vanishes as the transverse momentum of the J/Ψ increases.

- **Strangeness enhancement**

  The onset of thermalisation as well as more detailed quark-gluon plasma models lead to enchanced strangeness production for nuclear collisions, in comparison to pp collisions.

An increase of strangeness production has been measured. Ratios like K/π and inclusive φ, Λ and $\bar{\Lambda}$ production turned out to be a factor 2-3 greater than the values found in p-p interactions at the same $\sqrt{s}$. In particular, at $\sqrt{s} = 20$ GeV, it has been found $K^+/\pi^+ \approx 0.05$ in p-p interaction, while central S-S collisions at the SPS give 0.15 ± 0.03 at midrapidity and central S-W collisions give about 0.2. Also a strong increase in multi-strange baryon production has been found (for example, the $\bar{\Xi} / \Xi$ ratio from S-W collisions is surprisingly large with respect to the value obtained in p-p) .

- **Hard jets**

  The energy loss of a hard parton will presumably increase in dense hadronic matter, in comparison to p-p collisions, where the nucleon passes through the vacuum ("jet quenching"). Recent calculations for jet production in a "deconfining medium" found very little damping ("jet unquenching"). So a change in the jet production could signal a change of state of the medium through which it has passed.
- **Exotica**

  A deconfined phase could be also signaled by the direct appearance of an unusual form of matter: *droplets of strange matter*, manifested as baryonic states with very low charge to mass ratio.
- **P_T spectra**

  In general, the collective flow due to expanding matter leads to broadened P_T distributions.

Changes in the P_T spectra have been observed, compared to nucleon-nucleon collisions, reflecting rescattering phenomena.

All the above results point in the direction of the production of a dense, thermalized medium.

3.3 Conclusions

In summary, the following points have so far emerged from the experimental results:

- strong nuclear effects have been observed;

- all of them are specifically expected in the case of QGP formation;
- however, at present, alternative "hadronic" explanations are also possible.

As a consequence, we cannot claim to have obtained a unique, unambiguous signature of QGP, but rather a global pattern of phenomena typical for very dense matter. The new field of ultrarelativistic ion interactions has thus already provided very promising results.

4. EXISTING AND FUTURE FACILITIES: WHAT CAN WE LEARN?

In this section, the experimental facilities used in the context of ultrarelativistic heavy ion collisions will be examined with respect to their ability in providing answers about the *existence* and *properties* of strongly interacting matter under extreme conditions, i.e. hadron gas, phase transition and QGP. An assessment of both accelerators and experiments is given in the following separately for existing facilities, approved upgrades and planned future facilities. The main machine parameters are summarized in Table 2 together with some information concerning the scope of the corresponding programs. The *quality criteria* to be applied for accelerators are:

- attainable energy or baryon density
- range of available projectiles
- sensitivity (luminosity · running time).

The experimental programs should be able to address the observables listed in the previous chapters and will be assessed accordingly.

4.1 Existing facilities (AGS , SPS)

Accelerators. Existing accelerators provide an essentially complete coverage in center-of-mass energies from $\sqrt{s}$ 3 to 20 GeV/n. The maximum attainable energy density is of the order of the critical value $\varepsilon_c \approx 2$ GeV/fm^3 needed for a phase transition. The region of maximum baryon density at $y_{cm} = 0$ is expected to be in between the top energies of AGS and SPS for the projectiles presently available. Luminosity and running time are excellent at the AGS and mostly adequate at the SPS, but still marginal for some rare signals (J/Ψ). However, only light ions ("surface nuclei") can be accelerated so far, which severely restricts the volume and the lifetime of the intermediate states that can be studied at present machines. *The global assessment is therefore that existing accelerators are adequate in the covered range of $\sqrt{s}$ but heavier projectiles are certainly needed.*

Experiments. A summary of the experimental observables addressed by presently existing or approved detectors is given below. "Addressed" in this context means "adequate experimental capability", not necessarily published data. (*** good **adequate *poor - not covered). For completeness, results which are encouraging for QGP search or departure from a trivial superposition of independent nucleon-nucleon collisions are marked in a separate column as "positive results".

Signal	Addressed		Positive results
	CERN	BNL	
Energy density ε	***	***	+
Baryon distribution	*	*	+
Thermal γs	***	-	-
Thermal lepton pairs	***	-	?
Heavy quarkonia	***	-	+
Stable particle production (K,π,Λ,Ξ,p)	**	**	+
Resonance production (ρ,ω,η,ϕ)	**	-	+
Resonance spectroscopy (mass, width)	*	-	?
p_T-spectra	***	***	+
Fluctuations (average)	**	**	-
Fluctuations (event-by-event)	*	*	-
HBT	***	**	+
Exotica	**	**	-

With few exceptions, the present experimenal coverage, in particular at CERN, is good to reasonable. There is room for improvements, especially in the domain of large statistics, large acceptance detectors.

4.2 Approved new facilities (AGS + Au , SPS+Pb , RHIC)

Accelerators. With the advent of the new heavy ion injectors at Brookhaven (1992) and CERN (1994) and after completion of RHIC (1997), a *full spectrum of ion species* will be available for experimentation with essentially *complete coverage in energy* from $\sqrt{s}$ 3 to 200 GeV/n. The maximum energy density will increase by a factor of two at RHIC, the maximum baryon density could be within the range of the SPS (or slightly above), and the luminosity will increase by over one order of magnitude at the SPS. The luminosity at RHIC will be adequate for most signals, however, rare hard processes (Y, jets) will be only marginally within reach. *Therefore these new facilities constitute a significant improvement in all aspects.*

Experiments. *In the experiments proposed so far for the SPS Pb-program and for RHIC, all essential observables are covered adequately.*

4.3 Future facilities (GSI , KEK , LHC)

Accelerators. *Significant further improvements can be obtained at LHC* with Pb-Pb collisions at 6.3 TeV/n: a factor of two increase in energy density over RHIC, a large baryon free central region, and high luminostity and large cross sections for rare signals. For the foreseeable future, the LHC will be the *ultimate machine* to study the properties of an ideal plasma of quarks and gluons. The GSI and KEK proposals have the *advantage* of *dedicated colliders,* permitting systematic studies of projectile and energy dependence at comparatively ease. Their *physics potential,* however, as far as identifiable at the moment, is *largely covered* by existing machines.

Experiments. *No proposals have been made so far for experiments at these new machines.*

5. CONCLUSIONS

- *Specific and dedicated investigations in ultrarelativistic heavy ion collisions are in progress after an exploratory phase.*
- *So far, no unambiguous signature of QGP has been identified, but a pattern of signals indicating that we are in the right direction.*
- *Machines (existing, approved upgrades and planned) are adequate for majority of physics programmes.*
- *Experiments are largerly adequate, with room for improvements.*
- *Concerning specific needs, on the theory side, further studies of statistical QCD on larger lattices, as well as more detailed event generator studies are necessary. On the experimental side, large acceptance "hybrid" detectors covering different physics aspects are necessary. Moreover, systematic comparisons of nuclear collisions with p-p and p-A interactions, are necessary.*

6. RECOMMENDATIONS

1. The best possible preparation, the timely beginning and the optimal execution of the fixed target Pb-beam program for the CERN-SPS have the highest priority in the study of high energy nuclear collisions in Europe.

The Pb-beam at the CERN-SPS provides the unique opportunity of colliding really heavy nuclei at energies probably high enough to reach the deconfinement regime. To assure optimal preparation and execution of the experiments, sufficient funding for detector R/D and detector construction is vital. For conclusive investigations and to make best use of the facility, adequate running time is crucial. For a systematic exploration of the onset of the deconfinement transition, both the use of a variety of different A and experiments at different beam energies are essential.

2. The implementation of an adequate heavy ion program for the CERN-LHC, starting with the beginning of operation of the LHC, has the highest priority in the construction of future facilities for high energy nuclear collisions in Europe.

The LHC heavy ion program, on a time scale competitive to RHIC, provides a unique continuation of the SPS program into the domain of very high energy densities. It would make possible the exploration of an almost asymptotically free (ideal) quark-gluon plasma in a region of vanishing overall baryon density, and allow a full analysis of charmonium and bottomium spectra in dense matter.

3. In addition, it should be investigated as soon as possible if any new dedicated heavy ion facility would be able to address a unique physics program not covered by facilities presently available or under construction.

Any new construction could deviate manpower and funding from the SPS and LHC programs; this seems justifiable only if a new facility provides unique new opportunities not otherwise obtainable.

4. A European participation in the RHIC program can be supported with proper consideration of the SPS and LHC programs.

Here, as under 3, the deviation of resources should be discussed in the context of the SPS and LHC programs.

5. The character of the field, at the interface between nuclear and particle physics, reflects a major trend in modern nuclear physics. It needs the continued, strong and emphatic support and participation from the nuclear physics community in Europe.

TABLE 2

Existing and future heavy ion accelerators (some entries approximate only)

	AGS	SPS	AGS+Au	SPS+Pb	RHIC	LHC	GSI	KEK
Commissioning	1986	1986	1992	1994	1997	> 1998	?	?
A_{max}	^{28}Si	^{32}S	^{197}Au	^{208}Pb	^{197}Au	^{208}Pb	^{238}U	^{197}Au
E_{max} (Lab.) [GeV/n]	14.5	200	11.5	160	$21 \cdot 10^3$	$21 \cdot 10^6$	≈ 3000	≈ 50
$(\sqrt{s})^{nn} - 2m_n$ [GeV]	3.5	17.5	3	15.5	200	6300	50-100	≈ 10
$(\sqrt{s})^{AA} - 2Am_n$ [GeV]	98	560	580	3200	40000	$1.3 \cdot 10^6$	≈ 18000	≈ 2000
Rapidity range Δy	± 1.7	± 3	± 1.6	± 2.9	± 5.5	± 8.8	± 4.3	± 2.3
$(\frac{dn}{dy})^{nn} \approx 0.8 \ln \sqrt{s}$ (1)	1.4	2.4	1.3	2.3	4.3	7.0	3.5	2.0
$(\frac{dn}{dy})^{AA} \approx A^{1.05}(\frac{dn}{dy})^{nn}$ (2)	45	90	300	600	1100	1900	1100	500
L [cm^{-2}s^{-1}] (3)	$(10^9) \approx 10^{31}$	$(10^7) \approx 2 \cdot 10^{28}$	$(10^9) \approx 7 \cdot 10^{30}$	$(3 \cdot 10^8) \approx 4 \cdot 10^{29}$	$2 \cdot 10^{26} - 10^{27}$	$2 \cdot 10^{27}$	$>> 10^{26}$	$> 10^{25}$
Operation [weeks/year]	4-6	0-6	8-10	> 6	≈ 40	≈ 4	≈ 40	?
Users (4)	300+80	350+200	≈ 380	≈ 400	≈ 300	?	?	?
Experiments (5)	4+2+10	6+8+12	1 big new	4-6 big	2-3 big	1	2	1-2
Cost for ion part [M$]	25	5	30	30	300	?	?	≈ 50

(1) Rapidity density (charged + neutral) for nucleon-nucleon collisions at $y = 0$.

(2) Estimate of the rapidity density in central A-A collisions. The scaling exponent A^{α} is presumably in the range $\alpha \approx 1.0 - 1.1$.

(3) The Luminosity L of fixed target machines is calculated from the number of ions/burst (number in brackets), assuming a 10% interaction length target for A-A collisions and correcting for the duty cycle.

(4) Number of users at AGS/SPS shown separately for electronic and other (typically emulsion) experiments.

(5) Numbers at AGS/SPS shown separately for big, small and completed experiments.