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Overview of Very-High-Energy Heavy Ions*

Background material presented at the Discussion Meeting
on an Inter-Regional Program for Very High Energy Heavy Ions
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Abstract

This review gives a capsule summary of some background fa and basic considerations relevant to possible use of the CERN ISR experiments with light ions.

DISCLAIMER

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S UNLIMITED

1. LABORATORIES ENGAGED IN HIGH ENERGY HEAVY ION RESEARCH

Table I lists the parameters of existing and projected heavy ion accelerators, above 1 GeV/amu.

The most advanced program is at the LBL Bevalac, which is presently being upgraded to provide beams of the heaviest ions. The experimental teams of GSI (Darmstadt) and INS (Tokyo) have played an important role in developing the Bevalac program. It is currently estimated that 220 scientists (113 full time equivalents) are engaged in the nuclear physics research program. In addition there is a biomedical program and a cosmic ray and planetary science program.

The Dubna Synchrophasotron has a very active program with light ions ($Z \leq 10$) at a somewhat higher energy. There is a plan for a new injector to provide beams of much heavier ions.

Saturne, at Saclay, will enter the field as soon as the CRYEBIS source is ready. There is a plan to extend the capabilities of Saturne considerably by construction of a new injector, MIMAS.

The Numatron, at INS in Tokyo, will be a modern accelerator with energies and ions similar to the Bevalac but with much improved intensity and quality.

2. MAJOR PROPOSALS

GSI and LBL both have proposals for major new accelerators of substantially increased energy compared with the Bevalac.

SIS 100 would consist of two phases, with the room-temperature SIS 40 injecting into a superconducting second stage.

VENUS would include both a fixed target facility and colliding beams at an energy roughly 60% higher than the ISR.

Both accelerators would be dedicated facilities devoted to a very broad range of nuclear physics studies.

3. OPPORTUNITIES AT CERN

Opportunities have existed in principle at CERN for many years but implementation has been very slow because of priorities in the high energy physics program.

Examination of these opportunities is now urgent because of the planned closure of the ISR at the end of 1983, a decision mandated by the necessity to release funds for LEP construction.

It is timely also because of the recent $\bar{p}$-p run at the ISR and because of the GSI-LBL letter of intent submitted last October concerning a limited program of experiments with light ions at the PS.

The long delays involved in waiting for new construction to be completed elsewhere and the strong interest expressed in certain quarters make it interesting to consider even a short program at the ISR if it can be done quickly.

Because of the time needed to construct an appropriate injector, any program at the ISR would now require an extension of the life of that facility beyond 1983.

4. TYPES OF PHYSICS INVOLVED

The simplest way to classify the physics at the various accelerators is in terms of the rapidity distribution of secondary particles produced in the collisions.

It is observed experimentally that correlations between emitted particles occur primarily when the particles differ in rapidity by less than about two units (short-range order).

It is further observed experimentally that in a p-p collision three regions of the rapidity distribution are of special significance as illustrated in Figure 1.

In the Van Hove-Pokorski model, which is perhaps oversimplified but very useful, the quarks in projectile and target remain in the projectile and target fragmentation region respectively. The central region contains created particles.

This conceptual framework is borne out by the striking resemblance between the central regions in p-p and $e^+ - e^-$ collisions. The latter collisions do not involve incoming quarks at all.

The above discussion applies primarily to low transverse momentum processes, which dominate the multiplicity distributions. For these the Landau hydrodynamical model is very useful. It predicts for the central region a multiplicity N given by

$$N = k E^{1/2}$$

where E is the c.m. energy and k is a constant. This formula fits both $e^+ - e^-$ and p-p data very well if the latter are corrected for leading particle effects.

Particle production in p-p collisions rises with energy as shown in Figure 2.

High transverse momentum particles are relatively rare, are believed to arise from hard scattering processes, and must be considered separately. The properties of jets in p-p and $e^+ - e^-$ collisions are very similar. QCD gives a reasonable description of the hard scattering processes.

5. CLASSES OF ACCELERATOR

Figure 3 shows the rapidity interval available to the accelerators in Table I.

At accelerators in the Bevalac range the rapidity interval is sufficiently small that the target and projectile regions overlap. This is consistent with observations that it is possible essentially to stop the projectile nucleus in the target nucleus at these energies. In the Bevalac energy range new nuclear phases involving nucleon densities considerably higher than normal have been proposed. Perhaps states involving complete mixing of the quarks in target and projectile are possible.

At accelerators such as SIS 100, VENUS (fixed target) or the PS one is approaching the point where the quarks from target and projectile no longer overlap in rapidity so that new nuclear phases would most likely be reached by exciting one of the nuclei to a new configuration.

At energies such as are reached at the ISR or in the VENUS collider a well-developed central region may be expected. In this region new phases consisting entirely of created particles might been seen.

Once a clear separation is made between the three rapidity regions, little is to be gained by increasing energy, if short range order persists. However, for high transverse momentum processes, jet structures will become better defined as the energy increases.

6. PHYSICS OBJECTIVES

Objectives for study with nuclear as opposed to particle collisions can be stated in specifics or in general. Either

(a) To understand hadronic interactions currently expected to be explained by the color force;

At small momentum transfers to study the origin of confinement by looking for collective phenomena such as a transition to a quark-gluon plasma. To look for exotic multiquark objects produced in such a plasma;

At large momentum transfers to study the properties of quarks and gluons by allowing them to undergo secondary interactions in nuclear matter.

or (b) To study the space-time development of extended relativistic systems;
To study the conversion of energy into hadrons and vice-versa;
To study systems in which a high energy density is created over a large volume;
To study the nature of the physical vacuum.

7. WHAT TO EXPECT FROM NUCLEUS-NUCLEUS COLLISIONS

For the soft processes, Landau suggests that the number of particles produced will be proportional to the interaction volume at a fixed energy per nucleon.

If we assume that the volume of a nucleus is proportional to A and that the proton counts as a nucleus we will obtain an enhancement of a factor of A in equal mass collisions, as shown on the right hand scale of Figure 2.[+]

This enhancement is probably an overestimate, judging from cosmic ray data, but probably by less than a factor of 4 for Uranium Uranium collisions.

The number of particles within two units of rapidity is also of interest since these could all interact simultaneously if they were close enough in space. If ISR energies these will be of the order of 200 pions in such an interval, and 20 kaons. This raises the possibility of making interesting new particles by coalescence or other mechanisms.

At high transverse momentum it has been observed that p-nucleus collisions give a yield proportional to $A^{4/3}$ (roughly) while preliminary α-α data suggest $A^{8/3}$ for the nucleus-nucleus collision. The latter gave a yield 40 times higher than p-p collisions compared with an expected 16. For U-U collisions the yield would be 2.10^6 above the p-p yield.

8. SIGNATURES OF NEW EFFECTS

Study of spectra as a function of transverse momentum seems obvious. Figure 4 shows the scheme of Shuryak for identifying a possible phase transition.

Study particle production ratios--the strange particle yield is predicted to increase at a phase transition.

Study dilepton production at small transverse momentum to study the cooling down of the quark-gluon Plasma.

Look for new complex particles especially with multiple strangeness.

[+] This estimate differs from that which I gave in LBL-11974 and in the Proceedings of the workshop held in GSI, Darmstadt, October 7-10, 1980. My previous $A^{3/4}$ dependence was based on a misinterpretation of Landau's paper. Miraculously the $A^{3/4}$ dependence matches cosmic ray data and quark calculations by Brodsky or Bialas rather better than the A dependence. However evidence is scanty.

9. NECESSITY FOR BASIC INFORMATION

Even the simplest quantities such as multiplicity and rapidity distributions are essentially unknown, the only information coming from scattered cosmic ray, usually emulsion, experiments.

As the $\bar{p}$-p experiments at CERN have shown, even a slight increase in complexity of the system baffles our ability to predict in advance. Of course, in retrospect it is much easier.

10. A SMALL-SCALE PS AND SPS PROGRAM

A limited program of one-shot experiments (a few weeks per year over the next decade) can be foreseen for the PS and/or SPS if a new injector is built. GSI and LBL have already submitted a letter of intent which could lead to such a program.

This program could not, however, result in thorough and systematic investigation of the field. GSI and LBL have therefore, independently, chosen to seek funding for dedicated facilities which could be fully utilized for this and other areas of nuclear physics.

Dedicated facilities would allow optimization of accelerator parameters and detector systems, would permit very heavy nuclei to be accelerated and above all would be accessible for long periods of time.

Unfortunately the lead time in construction of such facilities means that experiments could not start at VENUS, for example, until about 1989.

This indicates the desirability of:

11. AN INTENSIVE SHORT-TERM ISR PROGRAM

Because of the desirability of early experiments, however primitive, utilization of the ISR would be worthwhile.

Since such a program cannot be started before the presently scheduled shutdown, it would have to justify the entire cost of operating the facility. This indicates an intensive short-term effort.

An ISR program would be limited in capability by its restriction to light nuclei and by the fact that the detector systems are optimized for p-p collisions, not for the much higher multiplicities in nucleus-nucleus collisions

Nevertheless it would provide basic information about nucleus-nucleus collisions which cannot presently be predicted. It would provide important learning experience for prospective users of dedicated facilities to come later. It might provide some exciting unexpected results.

While the more powerful accelerators on the drawing boards could be started at once if funds were made available, the design of detector systems would benefit enormously by a trial program at the ISR.

Thus both scientifically and technically, a short term program (even as little as one year if implemented intensively) would fit well into and help plans elsewhere for dedicated facilities . The possibility of early results of an exciting nature, even with light ion collisions, and even without the opportunity to develop a systematic program would justify the effort independently of those plans.

Acknowledgments

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This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

Table I. Existing and projected heavy ion accelerators above 1 GeV/amu. The accelerators are listed in order of increasing rapidity interval Δy. The beam momentum and rapidity interval are given for projectiles with Z/A=0.5. The last two entries, ISR and VENUS, are colliding beam facilities.

Accelerator	pc/A (GeV)	Δy	Status $Z \leq 2$	$Z \leq 10$	$Z \leq 100$
Saturne (Saclay)	1.8	1.4	now	1981	proj
Numatron (Tokyo)	2.6	1.7			proj
Bevalac (Berkeley)	2.9	1.8	now	now	1982
Synchrophasotron (Dubna)	4.5	2.3	now	now	1986
SIS40 (Darmstadt)	6.0	2.6			proj
PS (CERN)	13.5	3.4	now	proj	
SIS 100 (Darmstadt)	15.0	3.5			proj
VENUS (Berkeley)	25.0	4.0			proj
SPS (CERN)	200.0	6.1	(now)	(proj)	
ISR (CERN)	16.2	7.1	now	(proj)	
VENUS (Berkeley)	25.0	8.0			proj

Figure Captions

Fig. 1 Distribution of particle yields in a very high energy p-p collision as a function of rapidity.

Fig. 2 Particle yields (number of particles per collision) measured for p-p collisions (left-hand-scale) and as projected for U-U collisions at the same energy per nucleon.

Fig. 3 The c.m. rapidity of target and projectile is shown by the outer curve as a function of $\gamma_{c.m.} = E_{c.m.}/m$. The inner curve shows the separation of projectile and fragmentation regions from each other and from the central region. The maximum values of $\gamma_{c.m.}$ for the accelerators in Table I are indicated.

Fig. 4 Regions of transverse momentum according to the scheme of Shuryak.

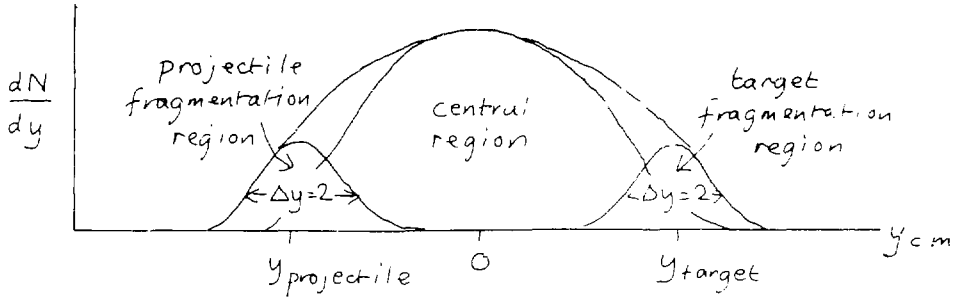
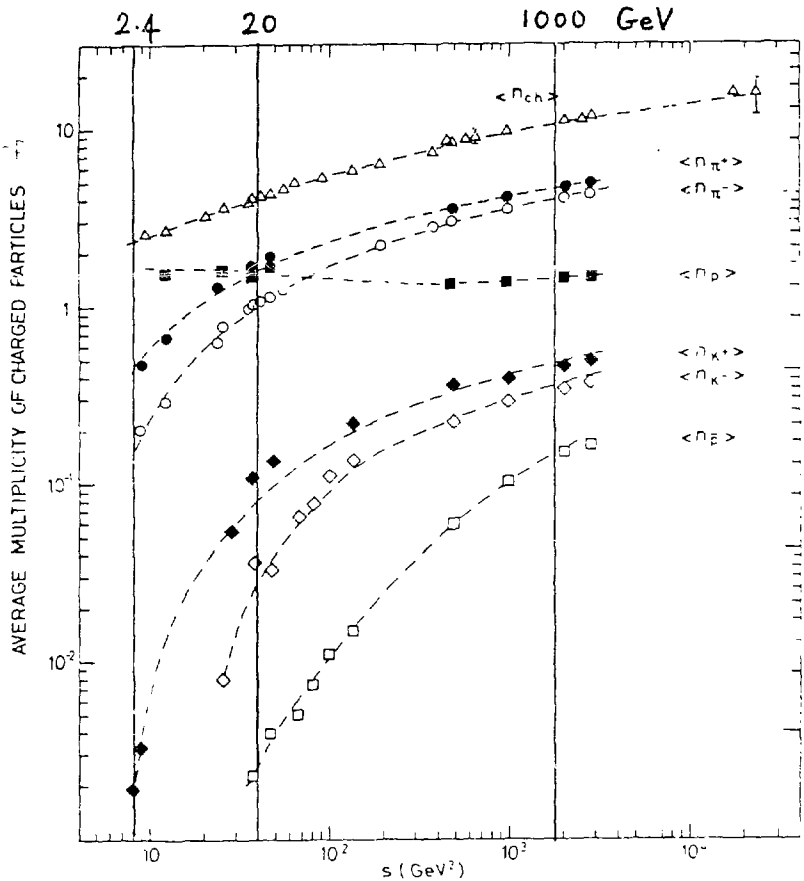

dN/dy
projectile fragmentation region
central region
target fragmentation region
Δy=2
Δy=2
y projectile
0
y target
y c.m

Figure 1


2.4
20
1000 GeV
AVERAGE MULTIPLICITY OF CHARGED PARTICLES
s (GeV²)
<nch>
<nπ+>
<nπ->
<np>
<nK+>
<nK->
<np̄>
10
1
10⁻¹
10⁻²
10
10²
10³
10⁴

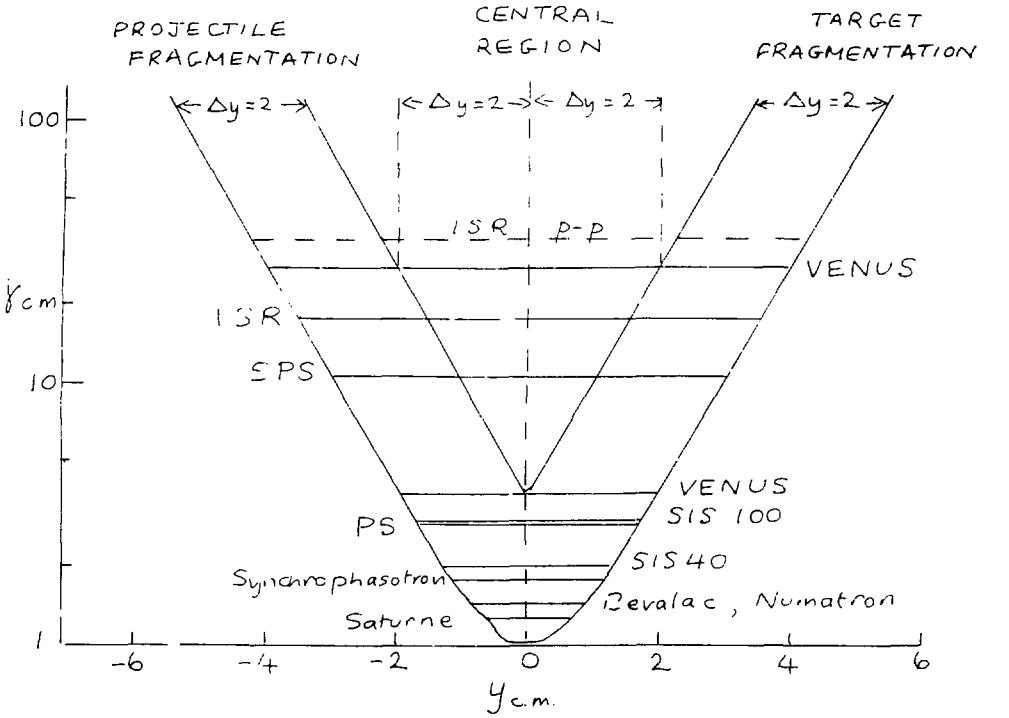

PROJECTILE FRAGMENTATION
CENTRAL REGION
TARGET FRAGMENTATION
Δy=2
Δy=2
Δy=2
Δy=2
100
10
1
γcm
ISR
p-p
VENUS
ISR
SPS
VENUS
SIS 100
PS
SIS 40
Synchrophasotron
Bevalac, Numatron
Saturne
-6
-4
-2
0
2
4
6
ycm.

Figure 3

HIGH TRANSVERSE MOMENTUM STUDIES
IN PROTON-PROTON COLLISIONS (Shuryak)
(ISR--Fermilab)

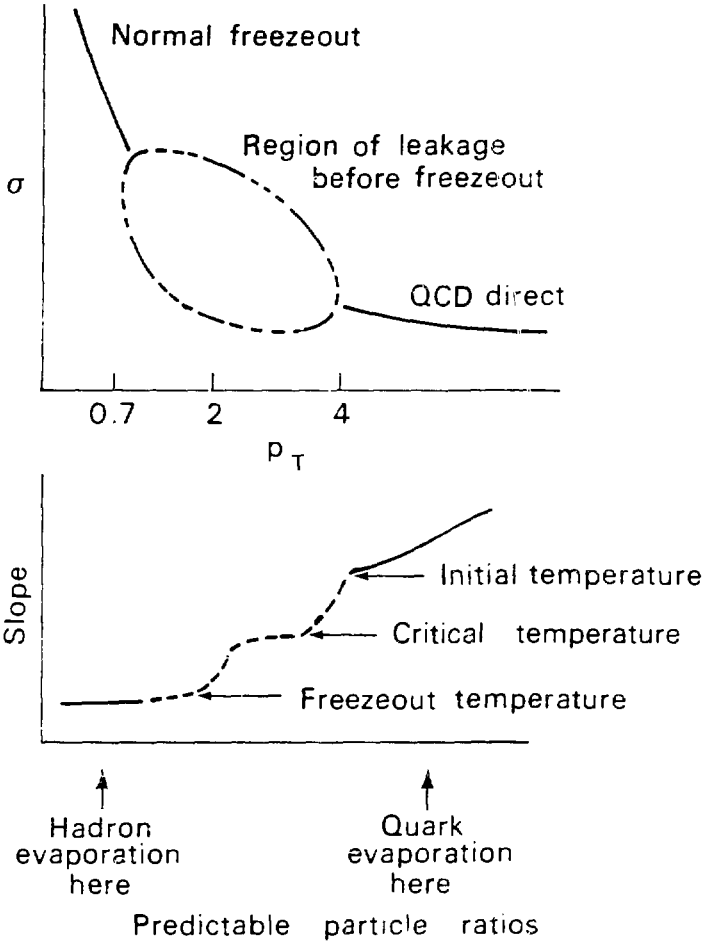


Figure 4