Presented at the Fourteenth LAMPF Users
Group Meeting, Los Alamos, October 27-28, 1980

ULTRARELATIVISTIC HEAVY IONS

Howel G. Pugh

December 1980

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

DISCLAIMER

This book was prepared in an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the U.S. Department of Energy under Contract W-7405-ENG-48.
The figures were printed from originals provided by the author.

ULTRARELATIVISTIC HEAVY IONS

Howel G. Pugh
Nuclear Science Division
Lawrence Berkeley Laboratory, University of California
Berkeley, CA 94720, U.S.A.

1. Historical Development of the Field

Studies with ultrarelativistic heavy ions combine aspects of cosmic ray physics, particle physics, nuclear physics, astrophysics and cosmogenes s.

The leading theoretical concerns are the behavior of matter at very high-energy density and flux, the general behavior of space time in collisions, relativistic nuclear theory, and quantum chromodynamics.

The field has developed over a period of more than thirty years, since the first observation of heavy nuclei in cosmic rays and the major developments of understanding of high-energy collisions made by Fermi and Landau in the early fifties. In the late sixties the discovery of the parton content of nucleons was rapidly followed by a great extension of high-energy collision phenomenology at the CERN ISR and subsequent confirmation of the QCD theory. In parallel the study of p-nucleus and nucleus-nucleus collisions at very high energies, especially at the CERN PS, Fermilab and the Bevalac, and in cosmic rays demonstrated that studies involving the nucleus opened up a new dimension in studies of the hadronic interaction. It is now at a high level of interest on an international scale, with major new accelerators being proposed to dedicate to this kind of study.

An ultrarelativistic heavy ion can be defined as one whose rest mass can be ignored in comparison with its energy, as a first approximation. Figure 1 shows a head-on collision between two equal mass heavy ions of 20 GeV/amu in the c.m. system. The Lorentz contraction in the c.m. is

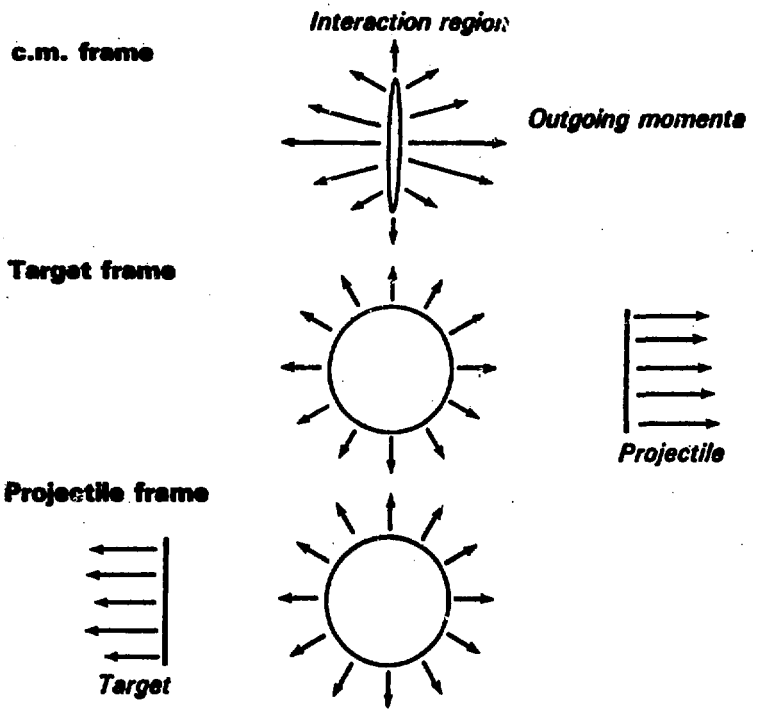
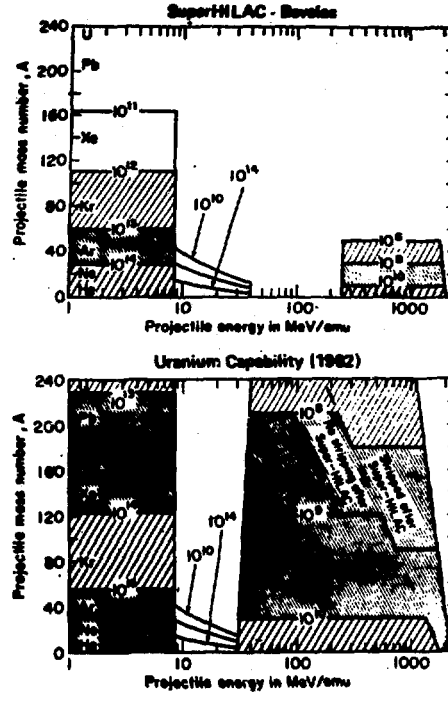


Fig. 1

approximately 1/20 so that the interaction volume is extremely small. In the target frame, the equivalent projectile energy is about 1 TeV/amu so that the projectile is contracted by a factor of about 1/1000 and has the proportions of a thin sheet of paper passing through the target. In the projectile frame the situation is reversed and the target nucleus apears contracted by a factor of 1/1000. Important features of the collision can immediately be deduced from such pictures, which show that in any reference frame a large number of nucleons in the colliding nuclei will act coherently as part of a single hadronic interaction of a nature inaccessible with collisions involving only single nucleons.

Current sources of information on high-energy heavy ion collisions include at relatively low energies the LBL Bevalac, with ions up to iron, and the Dubna Synchrophasotron, with ions up to oxygen. Soon we shall have light ion capabilities at Saturne II at Saclay and a full uranium capability at the Bevalac. Figure 2 shows the present and forthcoming capabilities of the SuperHILAC-Bevalac. It should be noted that the Bevalac is in the same energy per nucleon region as LAMPF. The Lorentz factor at the Bevalac is about three in the laboratory and two in the c.m. so the ions hardly yet qualify as ultrarelativistic. Particle creation is copious, however, already in Bevalac collisions, 15 pions being common in head-on Ar-Ar collisions.



XBL 8010-12223

Fig. 2

At much higher energies we have cosmic rays up to iron, proton-nucleus studies at high-energy accelerators, and limited but exciting experiments with colliding beams of deuterons and alpha particles at the CERN ISR. Propositions for new accelerators are seriously put forward in several countries, and several of them are almost approved. In a variety of energy ranges starting at 1 GeV/amu and extending to 1 TeV/amu, the major proposals are Japan's NUMATRON, the USSR's TYS at Dubna, Germany's SIS 100 at GSI

Darmstadt, and LBL's VENUS project which includes a colliding beam capability. There are serious moves to extend the CERN facilities to accelerate light ions heavier than alpha particles. All the other projects (except CERN) include beams of particles up to uranium.

2. Equation of State of Nuclear Matter

A major part of current interest in experiments with relativistic heavy ions results from their potential capability to explore properties of nuclear matter in regions so far totally unexplored. Figure 3 shows a phase diagram adapted from a paper by Gudima and Toneev[1]. Such a diagram implies that at each point there is some equilibrium description making an equation of state useful. The familiar region of this diagram is limited to a small area near $T = 0$ and $\rho/\rho_0 = 1$. The two lines show calculations of where transitions to new phases of nuclear matter may occur. Of special interest is the quark matter phase in which the quarks originally confined in individual nucleons become freed from their initial constraints.

In experiments on the nuclear system, neither the temperature nor the density is under control, as they would be for experiments on gases or liquids. However, high compressions and temperatures can be reached in heavy ion collisions. In Fig. 3 the line with the arrow shows the trajectory calculated by Gudima and Toneev for a head-on collision between an oxygen ion

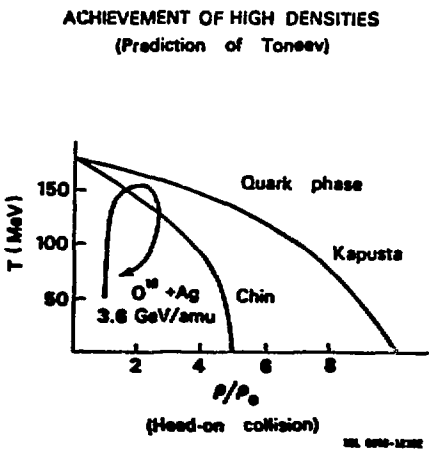


Fig. 3

and a silver target nucleus at 3.6 GeV/amu. The calculation shows that temperatures and densities are produced close to those required for a transition to quark matter.

To test these predictions, one can look at the temperatures produced by studying the energy spectrum of particles emitted from the collision in regions of phase space where direct scattering should be unimportant. Figure 4, adapted from a paper by Stocker et al.[2] shows temperatures deduced from proton and pion spectra at 90° c.m. in a variety of collisions. Very high temperatures are observed. It will be of great interest to determine if there is a limiting temperature and if it is the same as in p-p collisions. It will be of even greater importance to find ways to relate the transient phenomena observed in collisions to an equation of state applicable to stable systems.

If we turn to the low-temperature region of the phase diagram, many interesting possibilities have been discussed[3], as shown in Fig. 5. If there are

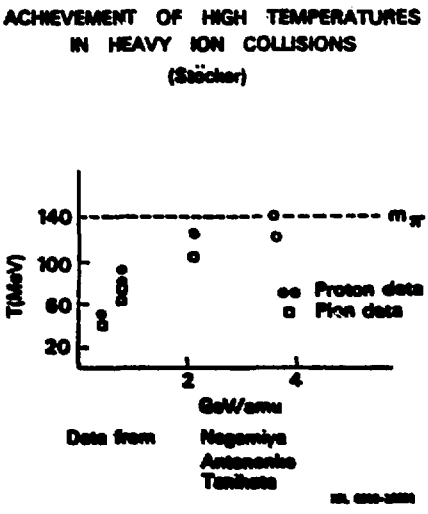


Fig. 4

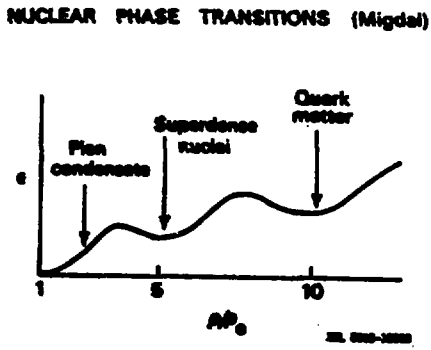


Fig. 5

local minima, stable or long-lived new states may exist, while the pion condensate would be of great importance in stellar evolution. At present there is little experimental evidence concerning these minima. A somewhat more mundane prediction[4], shown in Fig. 6, is surely accessible to experimental test. As the energy is raised the composition of the nuclear system changes, with a gradual shift from ground state nucleons to excited ones. Studies of precursor phenomena such as these may give more solid predictions of where phase changes may occur.

Shuryak[5] has recently reviewed these questions in a framework of quantum chromodynamics and has applied the theory to proton-proton collisions at ISR energies. Figure 7 shows his scheme for interpretation of inclusive spectra as a function of transverse momentum. Above 4 GeV/c the spectrum reflects the initial stages of the collision, i.e., the primary

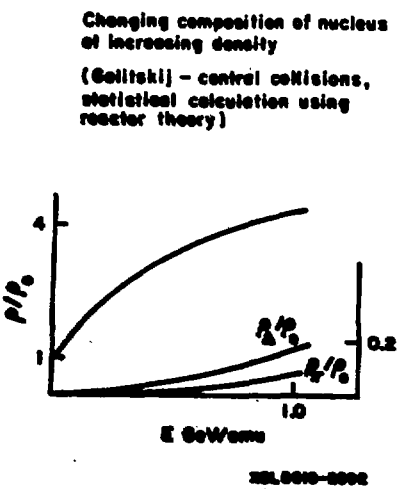


Fig. 6

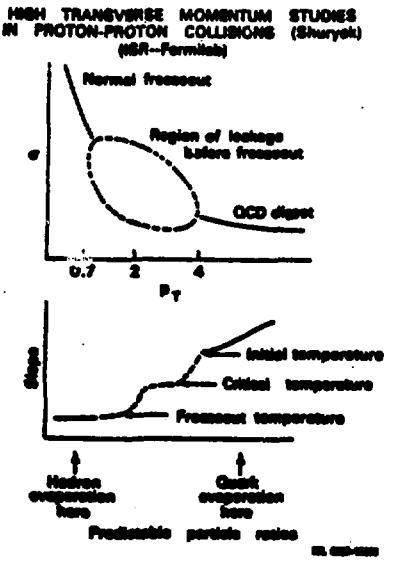


Fig. 7

quark-quark scattering. If the slope of the spectrum is interpreted as a temperature, that temperature is very high. At very low transverse momentum the particles observed are principally pions, the final products of decay of the created particles. This is called the freeze-out region. In the intermediate region, slope changes would signal phase transitions. It is of interest to note that in the p-p experiments the ratio of yields of observed particles changes in a predictable way with transverse momentum. Above 4 GeV/c quark-quark scattering predictions give a good account of the data.

3. Some Characteristics of Bevalac Collisions

To give an indication of the characteristics of studies using relativistic heavy ions, I will mention two experiments at the Bevalac.

Figure 8 shows some data taken with the streamer chamber[6] for approximately symmetric collisions (Ar on KCl) at 1.8 GeV/amu. The solid points show an unbiased selection of inelastic events. For each event the total multiplicity of secondary charged particles is measured (n_{tot}) as well as the total multiplicity of negative pions (which are easy to identify because of the negative curvature of the track in the magnetic field). It is interesting that charged multiplicities of 50 or more are common. Even after allowing for pion production it is clear that the total disintegration of both target and projectile into constituent nucleons must be quite common. The open circles show

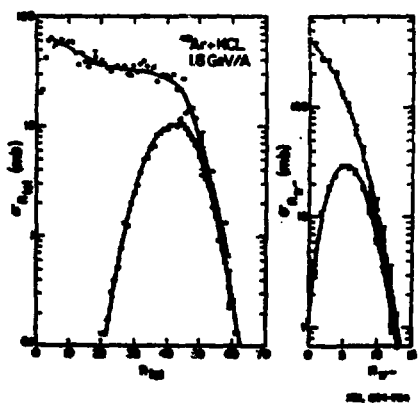


Fig. 8

events selected by an electronic trigger which uses plastic scintillators placed along the beam direction. Only events in which no part of the projectile continues at 0° are accepted. Such a trigger, designed to eliminate peripheral events, is clearly very effective in eliminating low multiplicity events and increases the average pion multiplicity. Surveys such as this have led to useful methods to characterize individual events, such as determination of the impact parameter. Second generation experiments proceed to study other properties of collisions at given impact parameter or secondary pion multiplicity.

While discussion of high density and high temperature have tended to focus on head-on collisions, one of the most interesting results has been in the forward angle region associated with projectile fragmentation and peripheral collisions. Figure 9 shows a characteristic series of collisions, induced by an iron nucleus in an emulsion. In work by Friedlander et al.[7] it was found that the interactions of secondary fragments do not occur with a simple exponential dependence on path length. Instead, about 5% of the

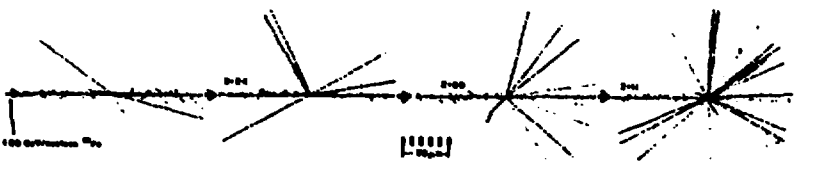


Fig. 9

fragments have anomalously short mean free paths. The corresponding cross sections are much larger than nuclear dimensions and defy conventional analysis. Following up these observations with other techniques is an important necessity.

New equipment is being installed at the Bevalac for the next round of experiments. This will proceed towards a more exclusive type of measurement. The next stage of 4π measurements will be with the GSI/LBL "plastic ball" which consists of over one thousand individual counter telescopes and will permit measurements of charged particles over 4π with energy measurement and particle identification below about 200 MeV/amu. A major new magnetic spectrometer, HISS, will be commissioned in 1981-82. It consists of a 2 m diameter, 1 m gap magnetic field of 3 Tesla, together with a very flexible detector system that can be arranged at the convenience of the experiments in many different ways. Figure 10 shows how it might be used for a study of correlations among projectile fragments. It is planned to reconstruct the effective mass of correlated groups of fragments with an accuracy of about 1 MeV. This should be useful not only in searches for exotic phenomena but in a wide range of conventional nuclear physics such as the study of giant resonances.

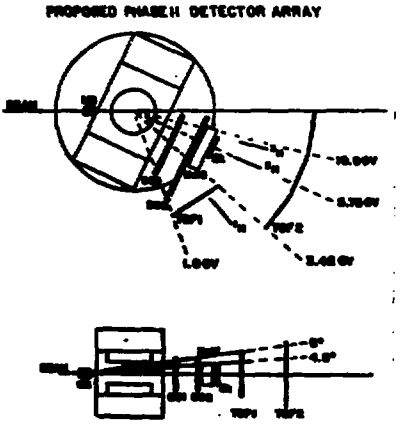


Fig. 10

4. Next Stages: Areas of Study

Three rather distinct areas of study will be accessible using the next heavy ion facilities. It is convenient to illustrate them using p-nucleus and p-p data.

Figure 11 shows total reaction cross section measurements below 500 MeV[8] and demonstrates that there are major effects below 200 MeV/amu but that asymptopia has set in by about 500 MeV/amu. In this asymptopia, scattering is dominated by single nucleon-nucleon collisions, quantum effects are minimal, and particle creation on a large scale has not yet set in. The low-energy region, characterized by this peak in the total cross section, is expected to be a rich area for study but is outside the scope of the present discussion.

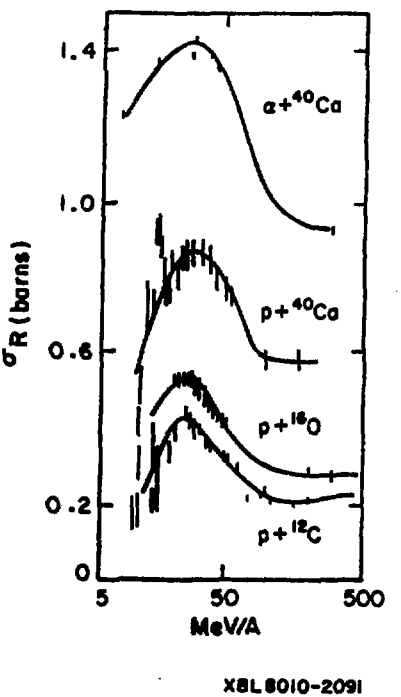


Fig. 11

The next energy region, up to about 10-20 GeV/amu in the laboratory, is the region in which any new states formed by recombining the quarks originally present in the target and the projectile. The reason for this is that at higher energies intranuclear cascading ceases due to the relativistic effects mentioned earlier. By 10-20 GeV/amu the nucleus appears to the projectile to be contracted to less than the thickness of a single proton.

Thus the excited hadronic system formed by a proton and the interacting parts of the target nucleus does not break up until it has left the nucleus, when the secondaries escape without further interaction. The cascading that is so effective in energy dissipation does not occur, and a description of the interaction in terms of the Van Hove-Pokorski model (in which the quarks in the target and projectile do not mix) becomes more applicable than any picture in which the target and projectile fuse to form a composite object. The transition is illustrated in Fig. 12, which shows the forward-backward asymmetry of secondary scandium fragments in p-uranium collisions[9]. By 10-20 GeV/amu an asymptopia is reached in which little energy and momentum are transferred from the proton to the residual nucleus. In the 1-10 GeV/amu region a much more complex interaction occurs.

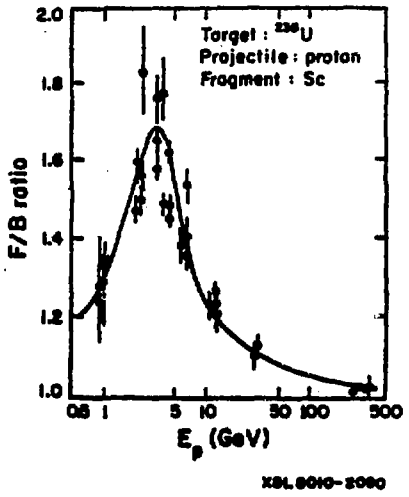


Fig. 12

The third region is the domain of colliding beam facilities, up to 1 TeV/amu where created particles dominate the reaction. By 1 TeV/amu the Lorentz contraction even in the c.m. system is a factor of 20 making this another natural objective for nucleus-nucleus collisions. At 1 TeV/amu it is possible to overlap two uranium nuclei completely in less than the thickness of a proton, creating enormous energy densities within a single hadronic interaction volume. This energy regime is characterized by an $E^{1/2}$ dependence of particle production once thresholds have been exceeded and by

the usefulness of extremely general thermodynamical arguments (Fermi, Landau, Hagedorn) to describe the general properties of collisions. It is this energy region which has been thoroughly explored at the CERN ISR for p-p̄ collisions.

Figure 13 shows particle production data at the ISR to illustrate how a new asymptopia is reached by about 1 TeV/amu.

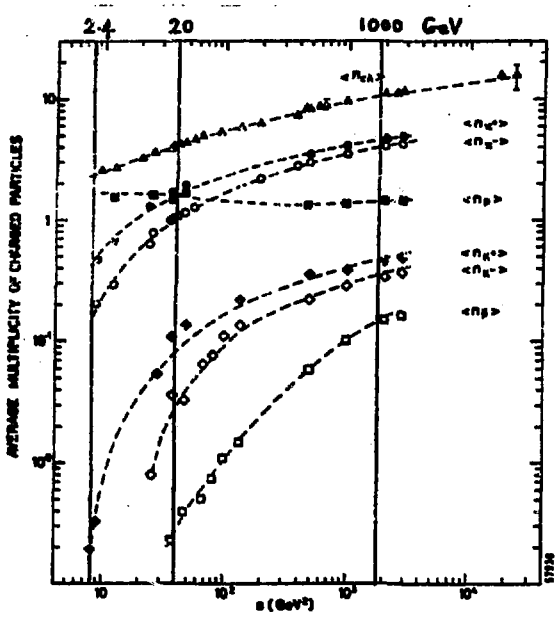


Fig. 13

Figure 14 shows how the various regions of physics are covered by LBL's VENUS project, and Fig. 15, adapted from a paper by Miklos Gyulassy illustrates in (a), (b) and (c) the approximations that are appropriate at different energies. Approximation (d), the Billiard Ball Limit, turns out to be qualitatively useful in all these regions, because it includes in a simple way the important geometrical and kinematical features which often dominate the detailed dynamics.

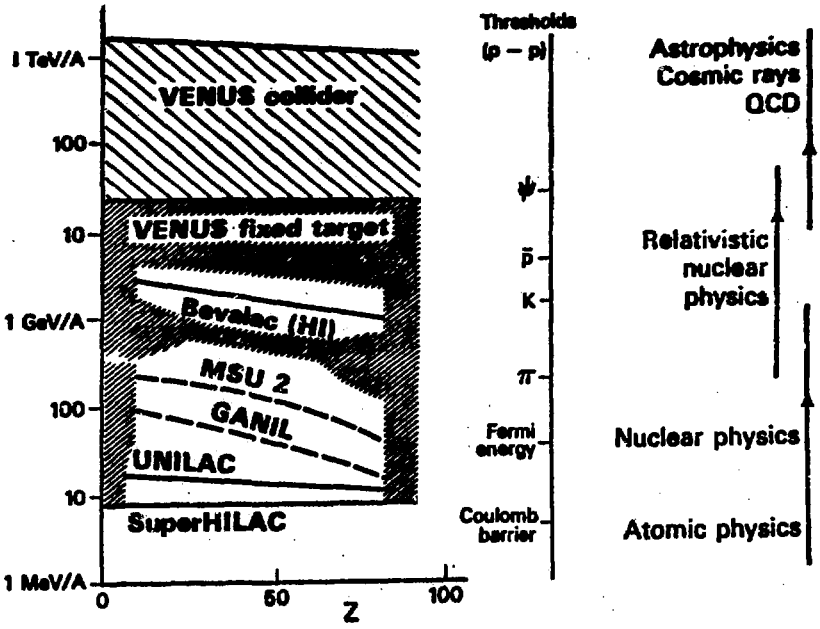

1 TeV/A
100
10
1 GeV/A
100
10
1 MeV/A
0
50
100
Z
VENUS collider
VENUS fixed target
Bevalac (HI)
MSU 2
GANIL
UNILAC
SuperHILAC
Thresholds
(p – p)
ψ
p̄
K
π
Fermi energy
Coulomb barrier
Astrophysics
Cosmic rays
QCD
Relativistic nuclear physics
Nuclear physics
Atomic physics

Fig. 14

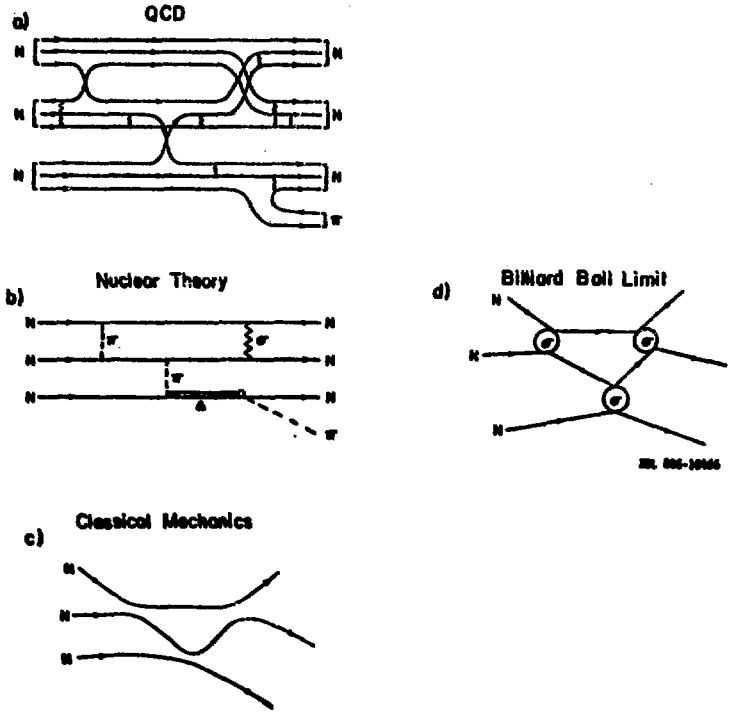

a)
QCD
N
π
b)
Nuclear Theory
σ
Δ
c)
Classical Mechanics
d)
Billiard Ball Limit

Fig. 15

5. Special Topic: Multistrange Systems

A subject receiving much current attention is the possibility that new systems containing large numbers of quarks might be stable. Figure 16 summarizes some predictions. A characteristic prediction is that the states of large negative strangeness would be the most stable. Thus Jaffe[10] has predicted that the dilambda would be stable, and Mann and Primakoff[11] have suggested that stages with B = 6, S = -6 would be specially stable.

PREDICTED MULTIQUARK SYSTEMS

e.g. Chin and Kerman
Bjorken and McLerran
Mann and Primakoff

- General Property of Predicted States —

  Long Lifetime
  Many Units of Strangeness

- B = 6 especially stable, with
  $n_u = n_d = n_s = 6$

  Superposition of

$$\begin{bmatrix} p & p & n & n & \Omega^- & \Omega^- \\ p & p & \Lambda & \Lambda & \Xi^- & \Xi^- \\ \Sigma^+ & \Sigma^+ & \Sigma^0 & \Sigma^0 & \Sigma^- & \Sigma^- \end{bmatrix} \text{ etc.}$$

  Comparable to α – Particle

- Possible Explanation of "Centauro" Event

  1 TeV Total Energy
  Absence of π^0 and Electrons
  Large p_T Secondaries

Fig. 16

It is therefore interesting to seek ways to create such particles, which may have some connection with the Centauro events observed in cosmic rays[12]. The conditions in a heavy ion collision at about 1 TeV/amu are probably the best we can ever reach for the production of such particles. Figure 17 shows the same data as in Fig. 13 with some extra scales added. On the left-hand scale is shown the number of secondary particles per event in p-p collisions, with the energy ranges of the Bevalac, VENUS and the ISR shown for comparison. To predict the particle production in nucleus-nucleus collisions, I follow the method of Landau[13] and scale using the multiplicative factor $A^{3/4}$. The result for U-U collisions is an increase in multiplicity by a factor of 60, shown on the right-hand scale.

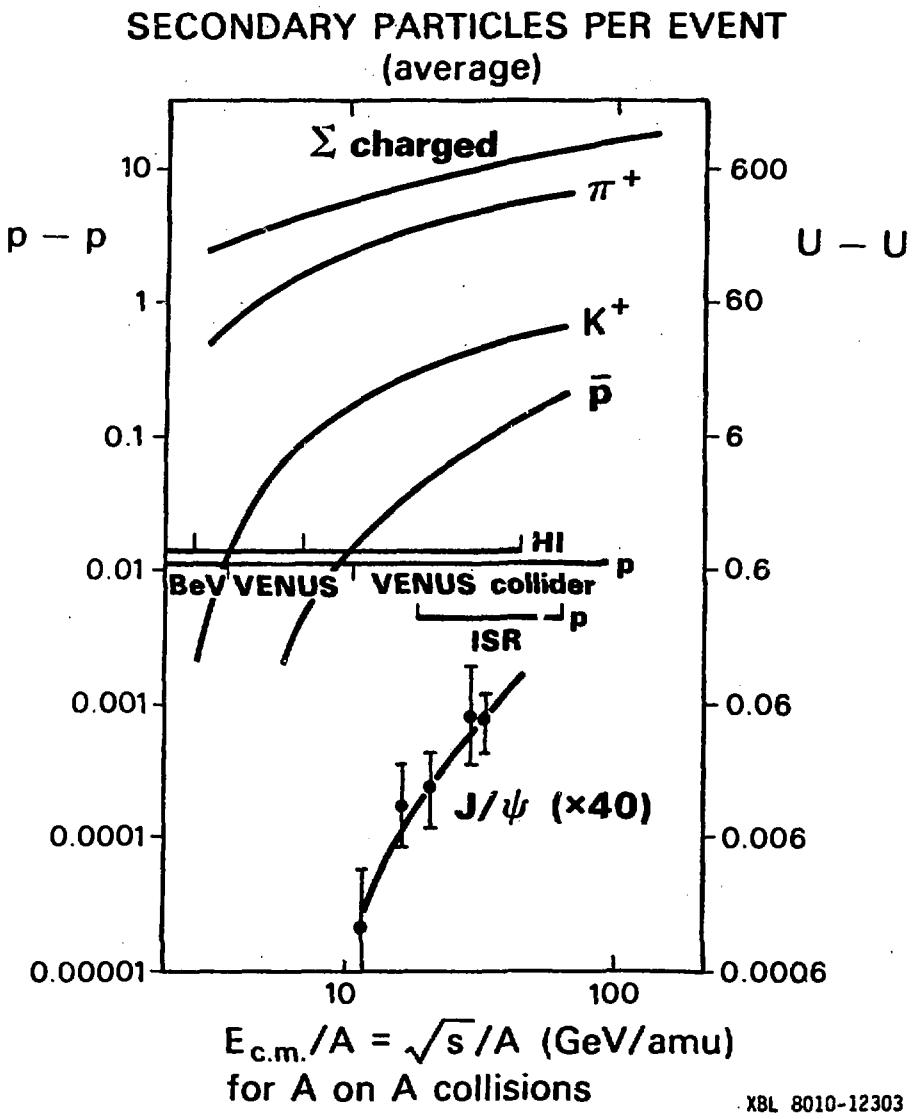

SECONDARY PARTICLES PER EVENT
(average)
Σ charged
π+
K+
p̄
p − p
U − U
10
1
0.1
0.01
0.001
0.0001
0.00001
600
60
6
0.6
0.06
0.006
0.0006
HI
p
BeV VENUS
VENUS collider
p
ISR
J/ψ (×40)
10
100
Ec.m./A = √s/A (GeV/amu)
for A on A collisions
XBL 8010-12303

Fig. 17

A collision between two 20 GeV/amu uranium ions will be quite an event. Figure 18 shows what we might expect: a head-on collision will produce even more secondary particles. The large number of kaons suggests that secondaries with large strangeness may be found in the debris. It is interesting to compare these results with expectations for other accelerators. Figure 19 shows that increasing A is much more effective than increasing E. In addition, a property of high-energy collisions is that the density of produced particles in rapidity space is roughly constant once asymptopia is reached. Thus increasing E above about 1 TeV/amu is unlikely to be rewarded by production of more complex particles.

TYPICAL EVENT AT VENUS

20 GeV/A Uranium on Uranium Qualitatively different from anything ever seen before in the laboratory.

Fig. 18

Average event will include emission of:

900	pions
90	kaons
10	antiprotons
476	baryons

The possibility exists for very unusual objects to exist in the debris from such a collision.

COMPARISON OF VENUS TYPE EVENT WITH THOSE AT OTHER ACCELERATORS

Secondary Particles Per Event $\langle n \rangle$

$$\langle n \rangle = 2.55\ E_{cm}^{1/2}\ A^{3/4}$$

Fig. 19

		$\langle n \rangle$
ISR	30 + 30 Protons	20
VENUS	50 + 50 Protons	26
ISABELLE	400 + 400 Protons	72
VENUS	4760 + 4760 U	977

Venus is Qualitatively Different

These discussions may suggest that the study of relativistic heavy ions is in some way in competition with particle physics in its search for the ultimate structure of matter. This impression would be a misleading one. Figure 20 shows some contrasts between the study of elementary particle physics and the physics of complex systems. Ultrarelativistic heavy ion physics is the heritage of nuclear physics, even if it concerns complex systems of quarks and gluons. It is a voyage of discovery in which

> "One does not discover new lands without consenting to lose sight of the shore for a very long time."
>
> André Gide

Contrast between Elementary Particle Physics and Physics of Complex Systems

Elementary Particle Physics

- search for smaller and smaller building blocks
- search for laws governing them
- concentration of energy at a point
- emphasis on simplicity

The results:

- often irrelevant for large systems
- difficult to apply in complex situations
- often lack predictive power because the possibilities are too many

Complex Systems

- may show coherent many-particle phenomena
- display a large variety of forms of stable arrangement
- are usually discovered rather than predicted
- often give new information on the components
- provide new opportunities for tests of fundamental laws
- frequently have useful applications

Fig. 20

Acknowledgements

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the U.S. Department of Energy under contract W-7405-ENG-48.

References

1. K.K. Gudima, V.D. Toneev, Dubna preprint E2-12624, 1979
2. H. Stocker, A.A. Ogloblin and W. Greiner, International Conference on Extreme States in Nuclear Systems, Dresden (1980); contributed paper p. 104

3. Adapted from invited paper by A.B. Migdal at Dresden conference (see above)

4. Adapted from invited paper by V.M. Galitskij at Dresden conference (see above)

5. E.V. Shuryak, contributed paper at Dresden conference (see above) p. 101

6. A. Sandoval et al. Phys. Rev. Lett. 45 (1980) 874

7. E.M. Friedlander et al. Phys. Rev. Lett. 45 (1980) 1084

8. R.M. Devries and J.C. Peng, Phys. Rev. Lett. 43 (1979) 1373

9. O. Scheidemann and N.T. Porile, Phys. Rev. C14 (1976) 1534. For discussion see H. Feshbach, 1st Workshop on Ultrarelativistic Nuclear Collisions, Berkeley, 1979, LBL-8957, p. 261 (1979)

10. R.L. Jaffe, Phys. Rev. Lett. 38 (1977) 195

11. A.K. Mann and H. Primakoff, Phys. Rev. D22 (1980) 1115

12. See, for example, G. Yodh, 1st Workshop on Ultrarelativistic Nuclear Collisions, Berkeley, 1979, LBL-8957, p. 139 (1979)

13. L.D. Landau, Izv. Akad. Nauk SSSR 17 (1953) 51; reprinted in English translation in Collected Papers of L.D. Landau, D. Ter Haar, ed., 1965, Gordon and Breach, New York