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Pugh, H.G.

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Introductory Remarks presented at the Workshop held at Gesellschaft für Schwerionenforschung, Darmstadt, West Germany, October 7-10, 1980

FUTURE RELATIVISTIC HEAVY ION EXPERIMENTS

Howel G. Pugh

December 1980

NUCLEAR SCIENCE DIVISION

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Introductory Remarks at the Workshop held at
GSI, Darmstadt, 7-10 October 1980

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

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

André Gide

1. INTRODUCTION

I would like to begin by thanking Professors Bock and Stock for organizing this workshop. It provides an opportunity to assess where we stand and where we are going. I would also like to thank Professor Zu Putlitz and Professor Bock for the strong and consistent support that they have given to this area of research: the GSI group at Berkeley has made a major contribution to development of the field of relativistic heavy ion physics, as has the theoretical group of Professor Greiner at Frankfurt.

The subject of the workshop is the future:

"Future, n.; that period of time in which our affairs prosper, our friends are true and our happiness is assured"

Ambrose Bierce,

The Devil's Dictionary

We need to discuss the experiments to be done in the near future, using accelerators that exist or are being built, and also the experiments that will need major new investment in new accelerators or detectors. For those who decide on such matters, I have two quotations:

"As for the Future, your task is not to foresee, but to enable it."

Antoine de Saint-Exupéry

The Wisdom of the Sands

"The future has waited long enough."

Adlai Stevenson

Present research with relativistic heavy ions has developed from early research into cosmic ray interactions, with strong fertilization from parallel developments in particle physics and nuclear physics. In recent years it has been strongly influenced by theoretical applications of ideas from nuclear and particle physics to questions in astrophysics and cosmogenesis. The leading questions are at the foundations of all these fields, and concern:

(a) Behavior of matter at very high energy density;

(b) General behavior of space-time in collisions at high energy flux;

(c) Relativistic nuclear theory and quantum chromodynamics.

In the following discussion, I shall focus on a few topics: I will discuss the question of equations of state for nuclear matter; I will discuss a few ongoing experimental studies; and finally I shall discuss the new opportunities with a few examples of physics to be learned.

2. EQUATION OF STATE OF NUCLEAR MATTER: HIGH TEMPERATURES AND PRESSURES

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 1 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. 1 the line with the arrow shows the trajectory calculated by Gudima and Toneev for a head-on collision between an oxygen ion and a silver target nucleus at 3.6 GeV/amu. The calculation was done with a cascade code, quite a reasonable method at this energy. For part of the interaction time,

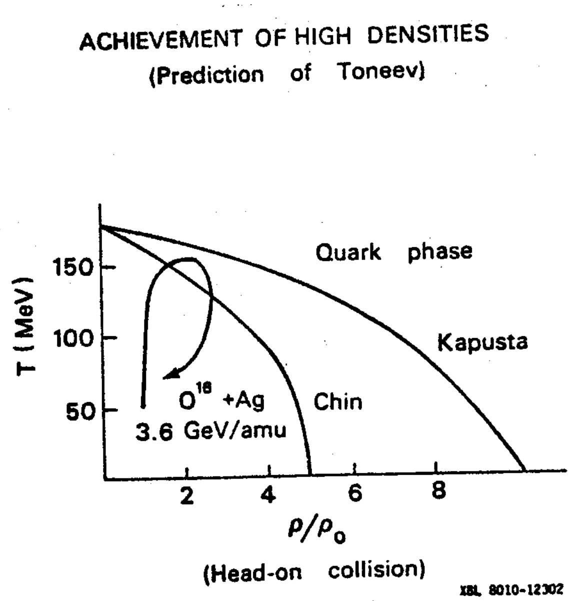

Fig. 1

this trajectory shows that temperatures and densities are produced close to those required for a transition to quark matter. We do not know whether the system remains under these conditions long enough to make a transition: it could remain in a superheated state. There is a great need for theories and experiments which can address the transient phenomena.

I do not know of any direct way to test for high density in a transient state. Some information on temperatures can be obtained by measuring the energy spectrum of emitted particles in regions of phase space where direct components should be small. Figure 2, adapted from a paper by Stocker et al.[2)] shows temperatures deduced from proton and pion spectra at 90^{0} c.m. in a variety of collisions. Very high temperatures are reached. It will be of great interest to determine if there is a limiting temperature in the Hagedorn sense and if it is the same as in p-p collisions. Questions associated with such an analysis are:

(a) Is the concept of temperature meaningful?

(b) If there is a quasi-equilibrated region, what is it? What, for example, was the impact parameter of the collision?

(c) Is the spectrum contaminated with particles whose velocities reflect the formation stage of the equilibrium?

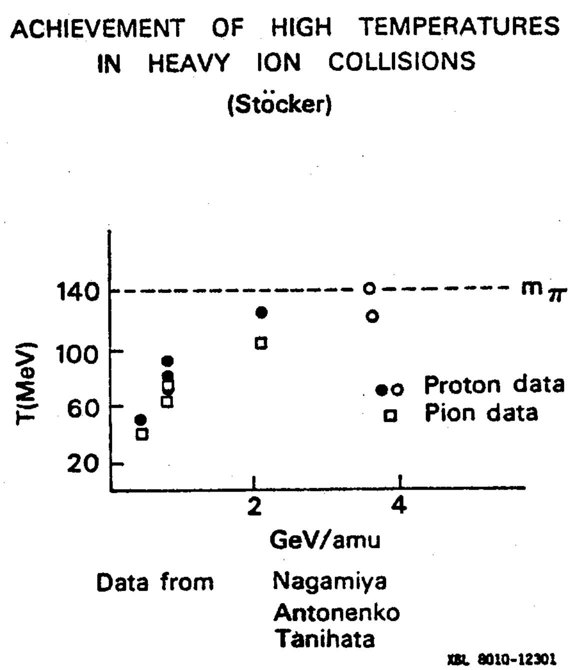

Fig. 2

(d) Do the observed particles represent the true temperatures reached or only some later "freeze-out" temperature?

Much further effort needs to be devoted to such questions by, for example, studying particles which might distinguish various stages of the collision or which might escape directly from the interaction region without secondary cascading or decay. The study of lambdas, photons and leptons springs to mind.

If we turn to the low temperature region of the phase diagram, many interesting possibilities occur[3)], as shown in Fig. 3. If there are local minima stable or long-lived new states may exist, while the pion condensate would be very important in stellar evolution. At present there seems to be little experimental evidence concerning these minima, though considerable theoretical attention has given us a much better understanding of what they would imply.

A somewhat more mundane prediction[4)], shown in Fig. 4, is surely accessible to experimental

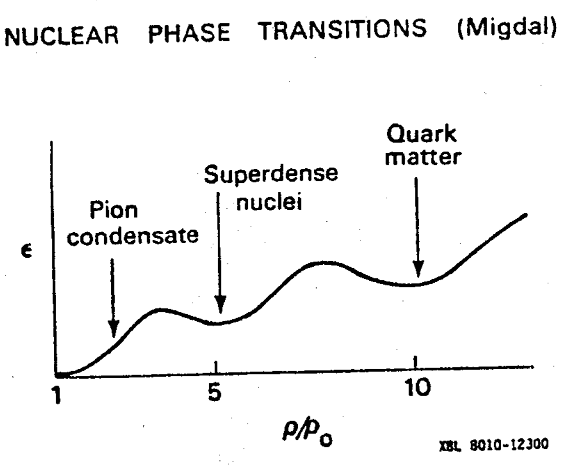

Fig. 3

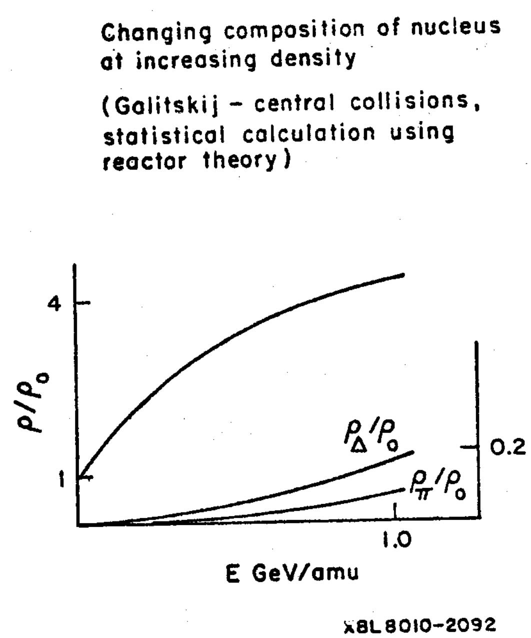

Fig. 4

test. As the energy is raised, the composition of the nuclear system changes, with a gradual shift from ground state nucleons to excited states. 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 5 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 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 possible phase transitions. Shuryak considers the p-p data suggestive in this regard but recommends experiments with nuclei to provide a more extended system in which a statistical discussion might be more necessary. It is of interest to note that in the p-p experiments the ratios of yields of observed particles change in a predictable way with transverse momentum.

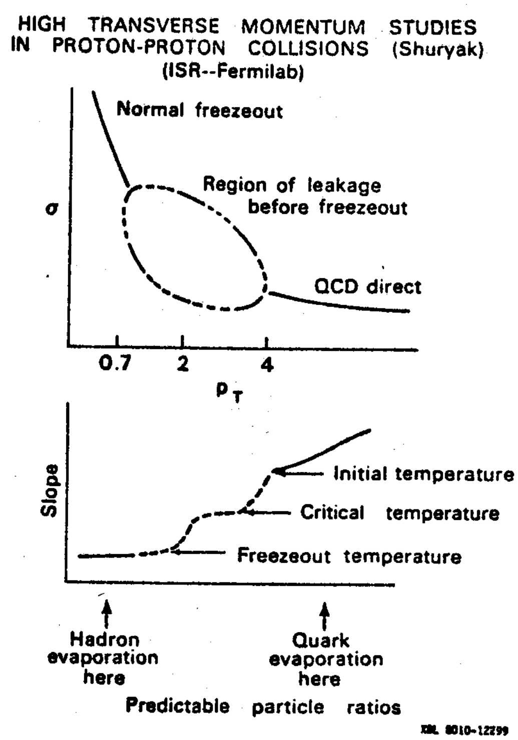

Fig. 5

Above 4 GeV/c quark-quark scattering predictions give a good account of the data.

3. SOME TOPICS AT BEVALAC ENERGIES

The capability of the Bevalac will shortly be much expanded, as shown in Fig. 6. New experimental and theoretical techniques will be needed.

On the experimental side, the identification of very heavy ions presents a challenge. We think we are ready for it. On the theoretical side the enhanced Coulomb interaction will introduce both complications and opportunities. Problems such as these require time and experience for their solution but do not present conceptual difficulties.

The availability of heavy projectiles will simplify some studies. As an example, the fragmentation of heavy targets by lighter projectiles will become easier to study when the roles of target and projectile can be interchanged, bringing the target fragments into an energy and angle region which is easier to measure. In this context a key problem will continue to be determination of the impact parameter for individual collisions.

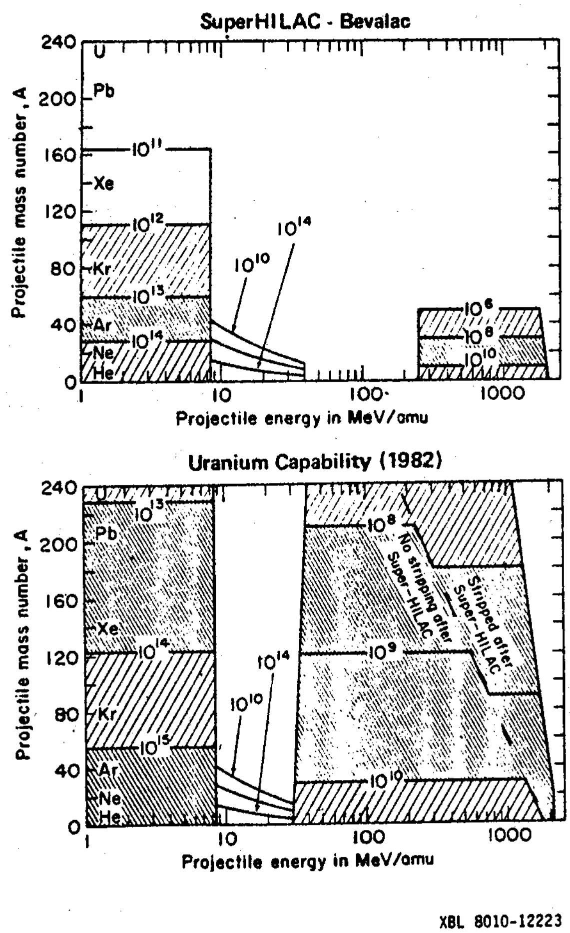

Fig. 6

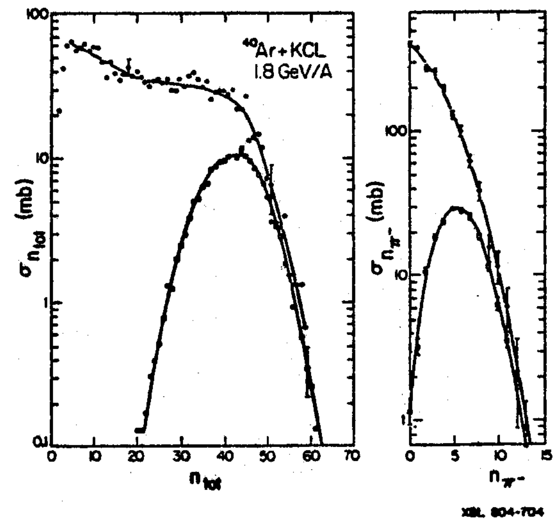

Fig. 7

Figure 7 shows some streamer chamber data from the Bevalac[6]. The data are for approximately symmetric collisions at about A = 40. The solid points show an unbiased selection of inelastic events. It is interesting that charged multiplicities of 50 are seen. Even after correcting for pion production it is necessary to assume that total disintegration of both target and projectile into constituent nucleons must be quite common. The systematics of such events are only now beginning to be collected and further study is obvious.

The open circles in Fig. 7 show events selected by an electronic trigger which uses plastic scintillators placed along the beam direction. Only events in which no part of the projectile survives within a narrow forward cone at 0^o are accepted. Such a trigger is designed to reject peripheral events and therefore for equal mass target and projectile to select central collisions. It is clearly successful in eliminating low multiplicity events and increases the average pion multiplicity. Correlations between different trigger conditions and associated multiplicities in different breakup channels will continue to be a powerful tool to investigate the reaction mechanism. Figure 8 shows predictions of proton multiplicities <m> by means of a cascade calculation[7]. It shows that proton multiplicities should be a reasonably good measure of impact parameter for equal mass collisions but that we will have to look for other criteria for unequal masses.

Discussions of high density and high temperature led us to focus on head-on collisions. We must be careful not to focus on them exclusively. As an example, I would like to mention the recent results of Friedlander et al[8)] obtained in the projectile fragmentation region. Figure 9 shows a characteristic series of collisions induced by an iron nucleus in an emulsion. 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 fragments have anomalously short mean free paths. The corresponding cross sections are much larger than nuclear

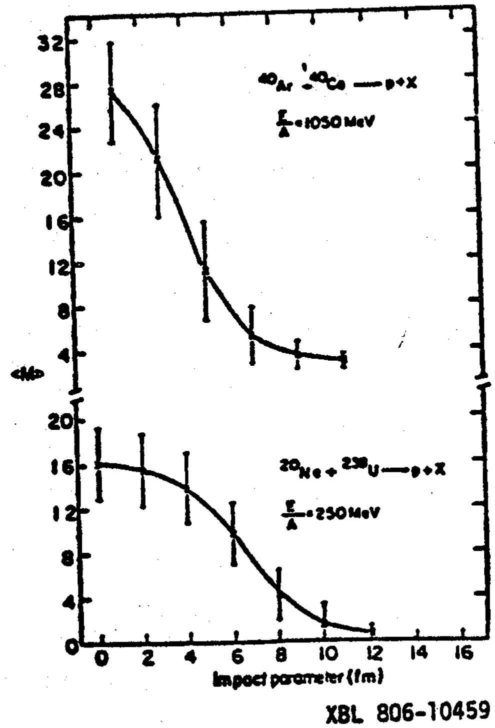

Fig. 8

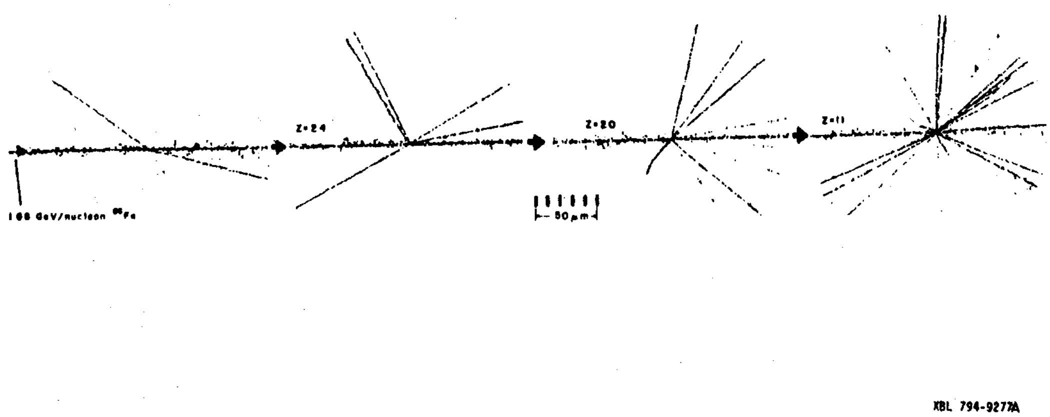

Fig. 9

dimensions and defy conventional analysis. Following up these observations with other techniques is an important goal.

The new equipment being installed at the Bevalac for the next round of experiments is designed to keep step with our progress towards a quantitative understanding of the phenomena which we uncover and to add the capability for a precise follow-up of specific new ideas. The next stage of 4π measurements will be with the GSI-LBL "plastic ball" which will permit measurements of charged particles over 4π with energy measurement and particle identification below about 200 MeV/amu. This will be able to pursue further collective phenomena such as the "bounce-off" effect predicted by nuclear hydrodynamical calculations[9)] and already indicated in associated multiplicity measurements[10)].

A major new piece of equipment to be commissioned in 1981-82 is the HISS spectrometer system, which 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 experimenter in many different ways[11)]. Figure 10 shows this detector as 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 very useful not only in searches for exotic phenomena but

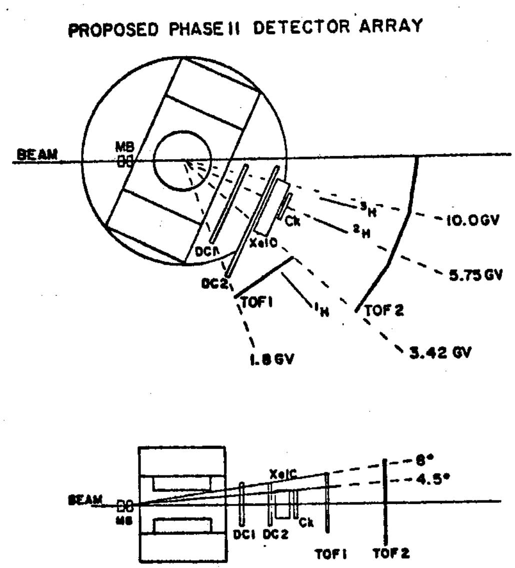

Fig. 10

in a wide range of conventional nuclear physics studies that have so far not been possible.

We look forward in this meeting to discussion of more complete detectors. We feel that in the long run it will be necessary to construct detectors at least as complex as those at high energy physics facilities. However, 4π complete measurements are more difficult with heavy ions and we hope that our present intermediate steps will be repaid not only by interesting experimental results but by a better understanding of design goals and necessities in the long term.

4. NEXT ROUND OF FACILITIES

Ideas for much higher energy heavy ion facilities have been developing for well over a decade. At Berkeley we have focused on needs for an eventual replacement of the Bevalac with a more powerful machine. GSI have a proposal, SIS 100, for a fixed target facility, while at CERN, despite enormous competition for beam time for elementary particle physics needs, there continues to be progress towards experiments using light ions. The recent alpha-alpha experiments at the ISR present a very exciting development[12)]. I shall present a thumbnail sketch of the kinds of physics to be addressed, in the framework of LBL's VENUS project[13)], which covers all the new energy regions of immediate interest.

Three energy regions can be rather clearly identified:

(a) $E < 500$ MeV/amu

This is the region of "conventional" nuclear physics. Figure 11 shows total reaction cross sections[14)] which illustrate that major effects occur in the 10-100 MeV/amu region while 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, including such thresholds as the Fermi energy and the energy corresponding to the velocity of sound in nuclear matter. Phenomena connected with density doubling are also accessible. Since any higher energy accelerator will of necessity be a synchrotron it will include this energy region, and extracted beams of high quality for nuclear physics studies should be made available. Several accelerators, e.g., CERN SC, GANIL and MSU Phase II, will cover part of this energy region for light ions. The Low Energy Beam Line (LEBL) at the upgraded Bevalac will cover it for all ions but with beam intensity and quality sufficient for exploratory studies only in most instances.

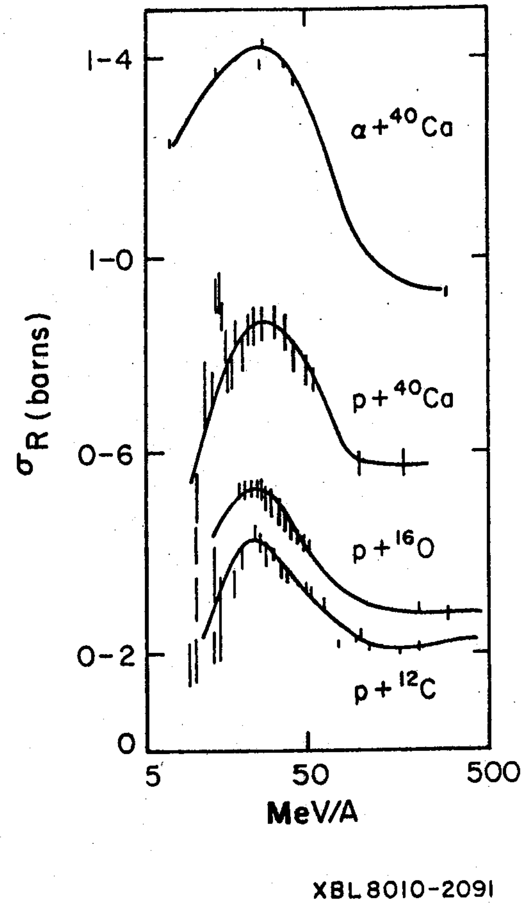

Fig. 11

(b) E < 10-20 GeV/amu

This is the region in which we are most likely to find any new states formed by recombining the quarks originally present in the target and the projectile.

In order to stop the projectile completely in the target nucleus, intranuclear cascading is necessary to dissipate the energy quickly. Even a few collisions produce equilibration. Because of the lack of suitable accelerators the phenomenology of stopping nuclei in each other has been little explored. However, Bevalac experiments and extensive p-nucleus experiments provide helpful information. As the energy is increased, cascading first increases due to the increased number of secondary particles. However p-nucleus studies show that as the energy is increased further cascading eventually ceases altogether. Thus we can expect that there will be some upper limit to the amount of energy that can be deposited in an equilibrated nuclear system at rest. This limit will be reached below the energy at which cascading ceases, about 10-20 GeV/amu.

The cessation of cascading is due to relativistic effects. In terms of time dilatation it can be stated that the time scale for the hadronic interaction to be completed becomes longer than the time taken for the particle to pass through the nucleus. Thus the excited hadronic system formed by the 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. In terms of the Lorentz contraction of the target nucleus, the nucleus at sufficiently high energies becomes contracted to less than the thickness of the incident proton and interacts with it as an entity, not by a series of collisions. The Lorentz contraction is approximately E in GeV, so that by 20 GeV/amu even a uranium nucleus is not large enough for cascading to develop. The extension of these p-nucleus considerations to nucleus-nucleus collisions is complex and conceptually rather difficult, but it is clear that at very high energies the nuclei will interact coherently and not as a collection of nucleons.

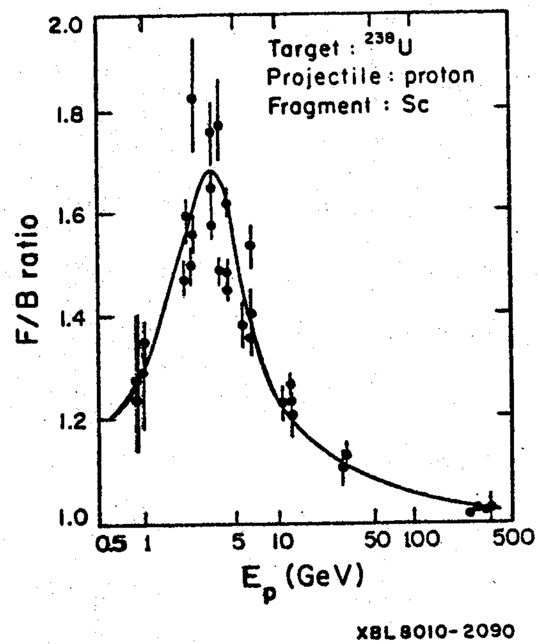

Fig. 12

Figure 12, taken from reference 15 illustrates the transition to the asymptopia characterized by absence of cascading, for p-uranium collisions. It shows the forward-backward asymmetry of secondary scandium fragments which characterize the decay of the residual nucleus after the interaction. At very high energies the results are consistent with very little transfer of energy and momentum to the fragments while in the 1-10 GeV/amu region a much more complex interaction occurs as the result of cascading.

(c) 20 GeV/amu < E < 1 TeV/amu

In this third region created particles dominate the reaction. By 1 TeV/amu the Lorentz contraction even in the c.m. system is a factor of 20, making 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.

In the Van Hove-Pokorski model of this interaction regime, the quarks from target and projectile continue in their original forward and backward directions, while in the central region of rapidity space a great number of created quarks and gluons proliferate. This energy region 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-p collisions. There have been many suggestions over the years that the ISR should be used for collisions between light nuclei. One such suggestion, made in 1975, is included as Appendix A; it is of interest for its specificity. The objectives of that suggestion, as well as others, have now been embodied in LBL's VENUS proposal. In view of the long lead time in VENUS construction it would be extremely valuable to proceed with the necessary modifications to accelerate light nuclei at CERN. Despite the limited beam time to be expected, the rich environment of sophisticated detectors would be hard to reproduce elsewhere. The principal parameters of the VENUS proposal are given in Appendix B.

Figure 13 shows on its left-hand scale the production yields of secondary particles per event in p-p collisions, with the energy ranges of the Bevalac, VENUS and the ISR shown for comparison. It will be noted that π and K production have reached an asymptotic region, p production is not yet asymptotic and J/ψ production is still in a threshold behavior. To predict the particle production in nucleus-nucleus collisions, I follow the method of Landau[16)] and scale from p-p production at the same c.m. energy using the multiplicative factor $A^{3/4}$. The result for U-U collisions is an increase in multiplicity by a factor of 60, which is shown on the right-hand scale.

One may question the validity of this scaling procedure. It stands the best chance of success for π and K which already follow Landau's $E^{1/2}$ energy dependence. Cosmic ray observations seem to be generally consistent

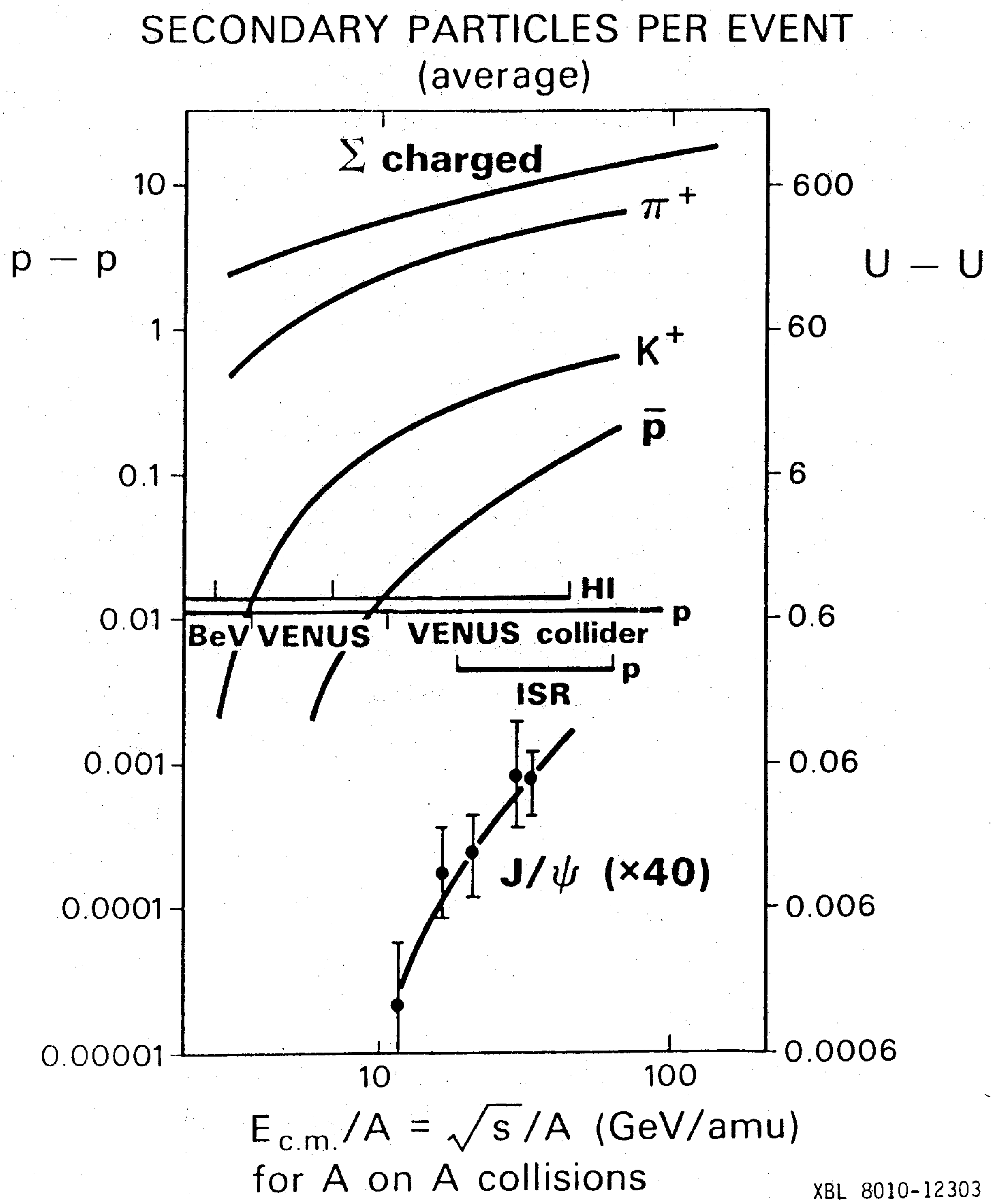

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Fig. 13

with $A^{3/4}$ scaling, as are microscopic theories such as those of Bialas[17] and Brodsky[18], within the kind of accuracy of interest at this point.

A collision between two 20 GeV/amu uranium ions will be quite an explosion. Figure 14 shows what we might expect for an average event; head-on collisions will produce even more secondary particles. The large number of kaons suggests that secondaries with large strangeness might be found in the debris. This would be of special interest because there have been several predictions of complex particles with large strangeness, as indicated in Fig. 15.

Predictions of multiquark systems have in general been based on the bag model, though many of the considerations may be more general. The most bound states are those with large strangeness, and these are also the ones which would be most easy to detect. For example, Jaffe[19] has predicted that the di-lambda should be stable. Mann and Primakoff[20] have recently suggested that states with $B = 6$, $S = -6$ would be specially stable. It is possible that such

TYPICAL EVENT AT VENUS

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

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.

Fig. 14

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

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

  Comparable to α – Particle

- Possible Explanation of "Centauro" Event

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

Fig. 15

states have some connection with the Centauro events observed in cosmic rays[21].

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 16 shows a comparison between different approaches.

COMPARISON OF VENUS TYPE EVENT WITH THOSE AT OTHER ACCELERATORS

Secondary Particles Per Event <n>

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

		<n>
ISR	30 + 30 Protons	20
VENUS	50 + 50 Protons	26
ISABELLE	400 + 400 Protons	72
VENUS	4760 + 4760 U	977

Venus is Qualitatively Different

Fig. 16

Increasing A is very effective in increasing <n> whereas raising E is relatively ineffective. Furthermore the density of particles in rapidity space does not increase appreciably as E is raised, the additional created particles appearing as a result of the expansion of the rapidity space available.

The search for unusual particles is only one of the reasons for wanting to study this energy region. I have chosen it for discussion because specific experiments can obviously be designed which could be carried out in the presence of a large number of less interesting produced particles. I anticipate, however, that most of the early experiments will be to establish systematics for comparison with p-p collisions and with p-nucleus collisions. Attempts to understand these systematics in the framework of QCD would follow.

5. CONCLUSIONS

Relativistic heavy ion physics is the only opportunity to study in the laboratory the properties of extended multiquark systems under conditions such that the quarks might run together into new arrangements previously unobserved. The starting point, the study of nuclear systems under conditions of very high density and temperature, has led us into questions of a fundamental nature concerning the confinement of quarks, particle physics, nuclear physics and cosmogenesis. Several lines of further study are immediately clear, with increasing A, increasing E, and increasingly sophisticated detectors. New accelerators are needed, with the possibility of the CERN ISR providing a few early forays to help guide us along the way. Workshops such as this one will help us formulate our needs and the physics of the future.

Acknowledgment

This work was supported by the Division of Nuclear Physics of the U.S. Department of Energy under Contract W-7405-ENG-48.

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Appendix A: Contributed paper No. VI.B.7, p. 347, 6th International Conference on High Energy Physics and Nuclear Structure, Santa Fe, 1975.

VI.B.7

Heavy Ion Collisions at ISR Energies: Possibilities for Experimental Study

H. G. Pugh

Department of Physics, University of Maryland, College Park, MD 20742

There has been great excitement generated recently by the development of heavy-ion beams in the region of 2 GeV/nucleon, particularly at the Bevalac. At the same time the strikingly original theoretical work of Lee and Wick and of Chapline, et al. has provided strong motivation for work in this area. It is the purpose of the present paper to emphasize that heavy ion studies at much higher energies are a practical possibility for the near future and to urge that these possibilities be taken seriously in the planning and development of new and existing accelerator facilities.

The basic observation is that heavy ion collisions at vastly increased energies can be obtained using existing intersecting storage ring facilities. This was suggested as a possibility by Gottfried at the last conference in this series. Fully-stripped heavy ions in the CERN ISR would provide equivalent energies of about 300 GeV/nucleon and any new storage ring facility at 400 GeV would provide an equivalent energy of about 50,000 GeV/nucleon. Studies at CERN indicate that injection of deuterons or alpha-particles could be achieved almost immediately while injection of light ions up to Carbon or Nitrogen will require only moderate development effort. Injection of fully stripped Uranium ions is at present still a dream. However, for concreteness the following remarks will be focused on fully stripped Uranium collisions;

(1) Predictions of the interactions are extremely difficult and the main difficulties lie in lack of knowledge of the strong interaction itself: the studies will therefore cast light on the nature of the strong interaction.

(2) The general behavior of the collision is dominated by its extreme relativistic nature. At 300 GeV/nucleon the entire nucleus is compressed longitudinally into about 1/50 the thickness of a proton. Many nucleons will therefore interact at once with any nucleon in the other nucleus.

(3) For many features of the interaction the thermodynamic predictions of Landau may be the most reliable. Here the Uranium nucleus is treated like a large proton since it has about the same density. Scaling from ISR results for p-p collisions then permits some predictions to be made for U-U collisions.

It is suggested that the exploratory studies should be conducted with experimental configurations that are <u>identical</u> to those used for studies of p-p collisions. A comparison might be made of p-p, p-H.I. and H.I.-H.I. collisions at the same GeV/nucleon. Pion multiplicities in the central region might be studied: the Landau model predicts about 600 pions produced per collision for U-U at the ISR. Inclusive distributions should be studied. Streamer chamber studies of individual events should be made. It is remarkable to consider that with 1000 or so particles emitted in each interaction, angular distributions with good statistics will be measurable for individual events.

According to this preliminary program the only important changes in the high-energy physics program would be additional work at the injector end of the facilities and devotion of a limited part of running time to heavy-ion beams. The extra effort would be most appropriate at the more complex facilities such as CERN where beams from the PS, SPS and ISR would provide a very wide range of energies and experimental setups for a relatively minor additional expenditure.

Appendix B:

1. Summary of VENUS performance specifications

THE VENUS PROJECT

Fixed target mode:

10 MeV/amu to 20 GeV/amu; 3 beams independently variable in energy, duty factor and intensity.

Colliding beam mode:

1 GeV/amu to 20 GeV/amu (1 TeV/amu fixed target equivalent), 3 intersection regions.

Proton capability:

50 GeV fixed target or colliding beams (5 TeV fixed target equivalent).

2. Layout of one of the design options being considered

VENUS
RELATIVISTIC HEAVY ION ACCELERATOR AND STORAGE RING