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Past and Present of Nuclear Matter

H.-G. Ritter

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PAST AND PRESENT OF NUCLEAR MATTER

Hans-Georg Ritter
Lawrence Berkeley Laboratory
University of California, Berkeley, CA 94720

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PAST AND PRESENT OF NUCLEAR MATTER

Hans Georg Ritter

Nuclear Science Division, Lawrence Berkeley Laboratory
Berkeley, CA 94720

INTRODUCTION

The subject of nuclear matter is interesting for many fields of physics ranging from condensed matter to lattice QCD. Knowing its properties is important for our understanding of neutron stars, supernovae and cosmology.

Experimentally, we have the most precise information on ground state nuclear matter from the mass formula and from the systematics of monopole vibrations.[1] This gives us the ground state density, binding energy and the compression modulus κ ($\kappa \approx 210 MeV$) at ground state density. However, those methods can not be extended towards the regime we are most interested in, the regime of high density and high temperature. Additional information can be obtained from the observation of neutron stars and of supernova explosions.[2] In both cases information is limited by the rare events that nature provides for us.

High energy heavy ion collisions, on the other hand, allow us to perform controlled experiments in the laboratory. For a very short period in time we can create a system that lets us study nuclear matter properties. Density and temperature of the system depend on the mass of the colliding nuclei, on their energy and on the impact parameter. But this control has a price. The system created in nuclear collisions has at best about 200 constituents, not even close to infinite nuclear matter, and it lasts only for collision times of $\approx 10^{-22} sec$, not an ideal condition for establishing any kind of equilibrium. Extended size and thermal and chemical equilibrium, however, are a priori conditions of nuclear matter. As a consequence we need realistic models that describe the collision dynamics and non-equilibrium effects in order to relate experimental observables to properties of nuclear matter.

With those constraints, heavy ion collisions give us access to the study of nuclear matter over a wide range of temperature and density. New phenomena occur and boundaries are crossed opening up new degrees of freedom. At low temperature

and density we observe multifragmentation where the nucleus possibly undergoes a first or second order transition to the gas phase. At temperatures of the order of $100MeV$ and densities of a few times ground state density, excited nucleons start to play an important role and we enter the regime of resonance matter, while at yet higher energies partonic degrees of freedom become important. At the highest energy available now or in the near future, we expect a new form of matter, the Quark-Gluon plasma, to be formed. Thus as we increase the energy available with accelerators we push our limits of observation closer to the origin of the universe, the big bang. All these exciting subjects are the topic of this NATO Advanced Study Institute.

The study of high energy nuclear collisions started at the Bevalac. The lessons learned and the concepts developed are important and relevant for the work at lower and higher energies. I will try to summarize the results from the Bevalac studies, the highlights of the continuing program, and extension to higher energies without claiming to be complete.

THE PAST

Progress in the understanding of high energy heavy ion collisions at the Bevalac came as an interplay between experiments, theory development, and accelerator improvements. In the early stage, spectra were compared with simple thermal models, like the Fireball model,[3] with cascade models[4, 5] that treat the nuclear collision as a superposition of nucleon-nucleon collisions, and with hydrodynamical models.[6, 7] All the models reproduced the data within a factor of two to four, but there was no conclusive evidence, favoring or excluding any particular model.

Substantial improvements were made when the experiments became more sophisticated. The first 4π detectors, the Streamer Chamber and the Plastic Ball, were able to detect and identify most of the emitted charged particles and to perform global event analysis. This novel type of analysis made the identification of collective behavior possible. In a bulk matter picture part of the energy available in the center of mass is converted into thermal energy and part is converted into compressional (potential) energy. The relationship between thermal (E_{th}) and compressional (E_c) energy as a function of density is shown in Fig. 1 for temperature $T = 0$. This relationship is sometimes called the equation of state. A more detailed discussion can be found in

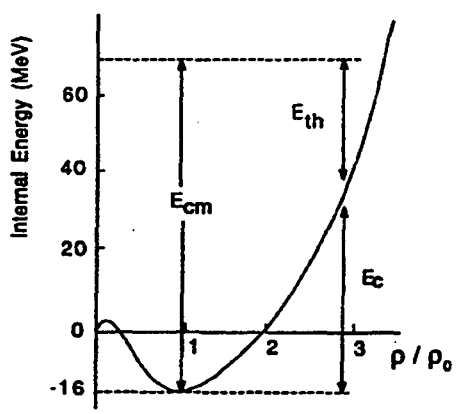

Figure 1. Energy per baryon as a function of nuclear matter density.

reviews.[8, 9]

In the expansion phase the compressional energy leads to collective flow. For events with finite impact parameter the flow should have a directed (non-spherical) component. This directed collective flow had been predicted by hydrodynamic model calculations[10] and was observed first by the Plastic Ball experiment[11] in $Nb + Nb$ collisions at $400MeV$ per nucleon.

The Streamer Chamber group followed a different approach. Their reasoning was that if there is potential energy in the form of compressional energy then it is not available for particle production, not at the point of maximum compression, nor during the expansion phase where it leads to collective flow. The group performed a systematic study of pion production,[12] and the basic idea to measure the available energy by studying particle production and sub-threshold particle production is still the basis for many experiments at GSI, at the AGS and at CERN. However, it is important to do careful comparisons with realistic models before any information about the reaction dynamics or about the property of nuclear matter can be extracted from those data.

In addition to collective flow the experiments revealed that in the most central collisions of the heaviest systems there were many indications that some kind of thermal equilibrium is achieved. The rapidity distributions[13] peak near mid-rapidity, as seen in Fig. 2 for the most central collisions, leaving no indication for the presence of

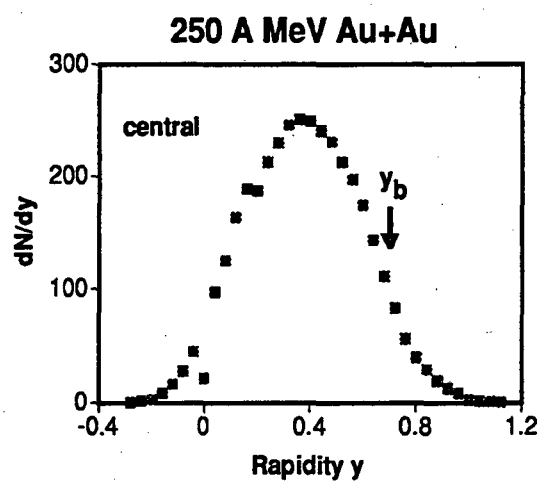

Figure 2. Rapidity distribution for baryons from Au+Au at 250 MeV per nucleon.

projectile spectators. Another indication for near equilibrium conditions comes from the measurement of the stopping ratio R, the ratio of the mean longitudinal to the mean transverse momenta of all the measured particles. A value of $R = 1$ indicates that the originally longitudinal momentum is distributed equally over longitudinal and transverse degrees of freedom. For the example of $Nb + Nb$ at $400MeV$ per nucleon[14] Fig. 3 shows that this condition is reached for the most central events.

Despite the great progress that was made on the experimental side it was not possible to unambiguously determine the equation of state. The concepts were too simple minded. Flow does not only depend on the static properties of nuclear matter (equation of state) but as well on the transport properties (viscosity). In addition, hydrodynamic or simple thermal models did not take into account non-equilibrium or finite-size effects. New microscopic models (VUU,[15] BUU,[16] and QMD[17]) including mean field effects, the Pauli principle, and momentum dependent interactions,

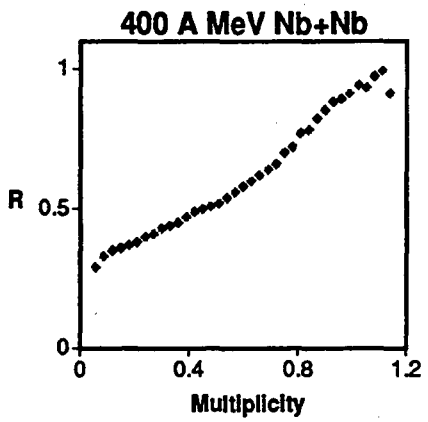

Figure 3. Stoping ratio R as a function of normalized charged particle multiplicity for Nb+Nb at 400 MeV per nucleon.

became available. This made a dramatic difference, since the shortcomings of the other models were overcome and information about the form of the equation of state is included via density dependent potentials. Now it was possible to predict a broad range of phenomena over the complete energy range of the Bevalac. As an example, Fig. 4 shows VUU predictions[18] for the energy dependence of the mean transverse momentum in the reaction plane[19] as a function of rapidity.

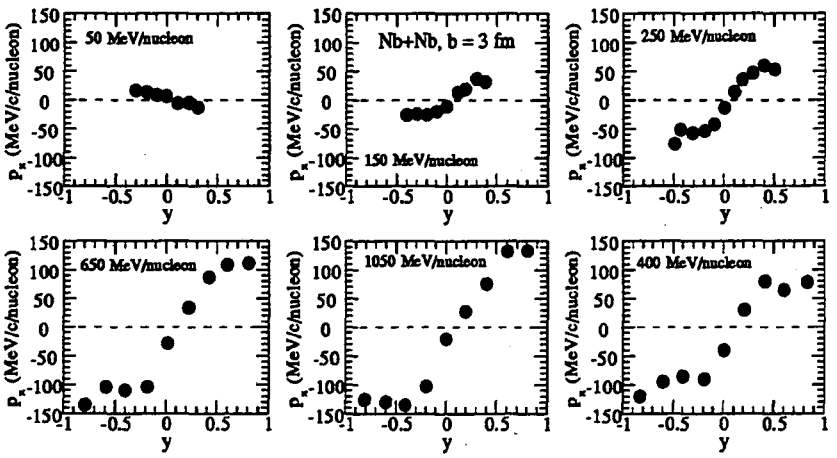

Figure 4. VUU predictions for the energy dependence of the mean transverse momentum in the reaction plane versus rapidity for Nb+Nb.

The very encouraging result from the rapid development in theoretical models is that the data of high energy heavy ion collisions are sensitive to the equation of state. However, observables are only sensitive to less than a factor of two at best, and the uncertainties in other parameters, like the modification of the in-medium cross sections or even the technical implementation of well known effects into the models, make a clear statement difficult.[20] It was very obvious that for the next step progress had to come from the experimental side with more precise and more complete data covering a large variety of observables over a large range of energy and mass.

THE PRESENT

In the past years a very active program has developed at many places. SIS at GSI has replaced the Bevalac as the main accelerator in what is now called intermediate energy ($\approx 100MeV$ up to $2GeV$ per nucleon). This new facility has made a big impact with three new second generation experiments, FOPI, ALADIN and KAOS. At lower energies MSU and GANIL complement the program.

Multifragmentation

At low energies we observe in the exit channel of nuclear collisions sequential binary decay. Above $\approx 35MeV$ (depending on the mass of the system) this mechanism changes[21] and many intermediate mass fragments are emitted,[22] a process that is called multifragmentation. Especially the ALADIN experiment has established the systematics of multifragmentation as a function of mass and energy.[23] The data have been used to test microscopic models that have been combined with statistical multifragmentation codes.[24] Many ideas have been proposed in an effort to explain the multifragmentation mechanism, among them the development of surface instabilities[25] and the formation of bubbles and rings.[26] It was suggested to see multifragmentation as a critical phenomenon quite a while ago[27]. The new data from the EOS experiment have been used in an attempt to extract critical exponents[28] by analyzing the data in terms of moments proposed by Campi.[29] All those new possibilities and ideas make multifragmentation one of the most interesting subjects with the potential to determine the nuclear equation of state at densities below ground state density and to study phase transitions in small systems. Such studies could lead to tools and methods that can be applied in the search for the Quark-Gluon plasma and in other areas of physics.

Flow

Flow is caused by the short range nuclear repulsion and its strength decreases with decreasing energy. At very low energy the attractive part of the nuclear potential becomes more important and the direction of the flow is reversed. This was first seen in the VUU calculations[18] shown in Fig. 4. This behavior is called disappearance of flow and has been observed experimentally.[30] This subject is covered in several contributions.[21, 31] The point where the flow is zero is called balance energy. It can be determined very precisely and is quite independent of detector biases. Detailed and systematic measurements of the balance energy as a function of mass have been performed. Fig. 5 shows a summary of these studies[21] and a comparison with BUU calculations. Fig. 5 indicates that the balance energy does not depend strongly on the equation of state. This is not astonishing, given the low density at those energies, but the effect is expected to depend strongly on the in-medium cross sections.[21, 32]

The detailed study of directed flow has been considered the best way to pin down some of the parameters of the nuclear matter equation of state. As a consequence systematic measurement have been performed in many experiments at many accelerators. As an example, the excitation function of the flow is shown in Fig. 6 where new results from EOS[33] are compared with the Plastic Ball data[34]. The EOS data show the increase of flow with energy much more clearly pronounced, differences especially at the high energies being most probably due to missing acceptance corrections in the Plastic Ball data. This trend is further highlighted by the analysis of the data

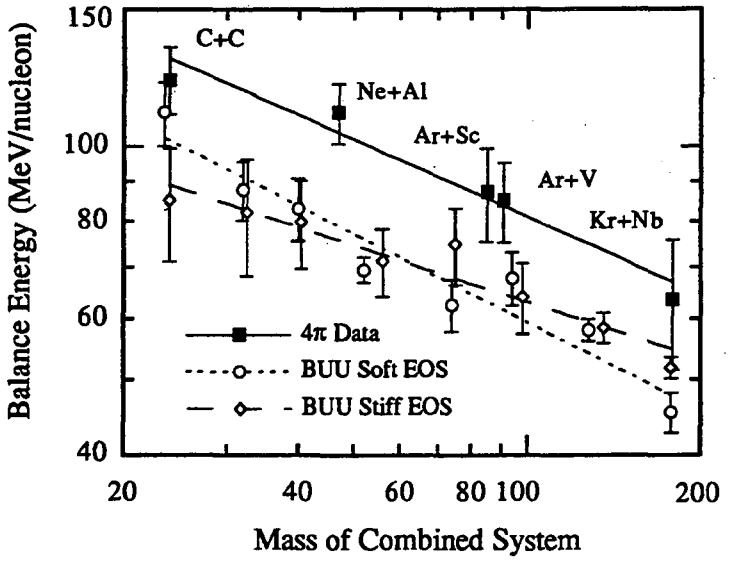

Figure 5. The balance energy as a function of the mass of the combined system is compared with BUU calculations with a soft and stiff equation of state.

in terms of hydrodynamic scaling.[35] In addition to the systematic study of the magnitude, new data and new methods allow us to ask if the flow signal is an effect of focussing the particles in the reaction plane, or of those particles having higher momenta, or a combination of both.[33] Another encouraging sign of progress is that systematic comparisons with different models now are being done routinely.[36]

Composite particles show larger flow effects.[22] In a thermal picture, the mean kinetic energy of all particles is the same, which means that the mean energy per nucleon decreases with increasing mass. The collective boost from flow, however, is independent of fragment mass and therefore becomes more important with increasing mass. The FOPI collaboration has emphasized the importance of the fragments in their systematic analysis of directed fragment flow[37] and in the exciting new evidence for "radial" flow.[38]

The energy contained in directed flow is only a few percent of the total available kinetic energy.[11, 36] From entropy considerations[39] and from general energy estimates,[40] we would expect to see a much larger fraction of the total energy contained in collective flow. With a large dynamic range in fragment mass coverage, the FOPI collaboration was able to plot the mean kinetic energy per nucleon as a function of fragment charge as shown in Fig. 7. The data (open squares) do not follow the pattern expected from a purely thermal source with Coulomb corrections (triangles). Instead, they follow closely the predictions from a thermal model with isotropic radial flow (circles), and for large masses the mean kinetic energy per nucleon seems to saturate. The large difference between the data and the thermal expectations can be taken as an indication for the presence of a large amount of collective flow.

The data presented in Fig. 7 are from the most violent events with very stringent cuts on centrality and are taken within a limited range of emission angle in the center of mass system. Therefore, it is not possible to distinguish experimentally between radial (isotropic) flow and azimuthally symmetric flow perpendicular to the beam axis, the limiting case of directed flow for very central events. Since the energy contained in this new type of flow is much larger than the energy contained in directed flow,

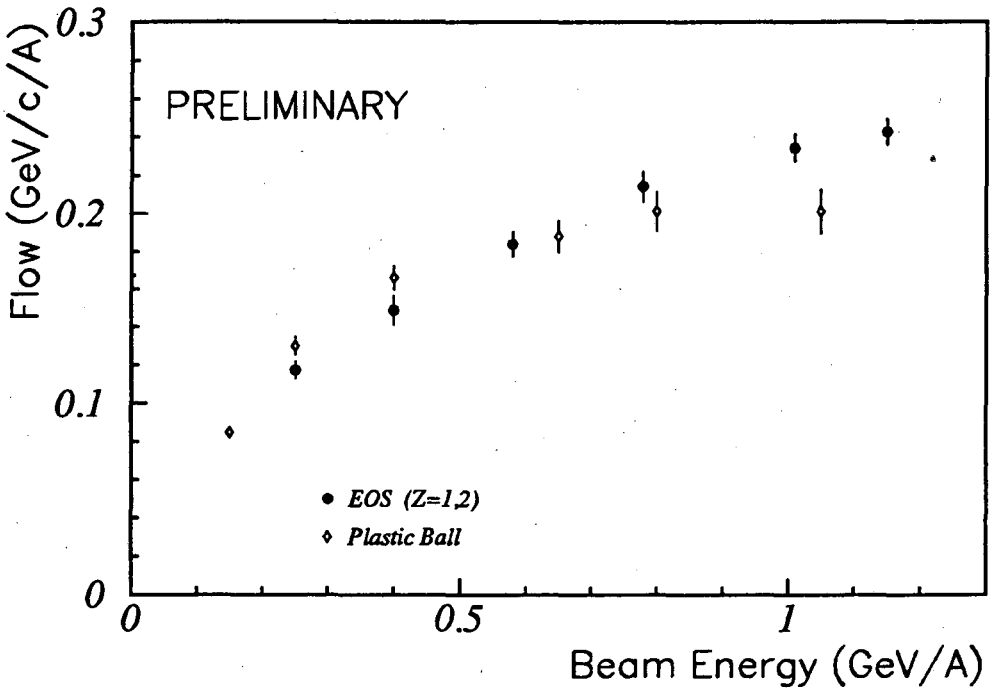

Figure 6. Flow results from Plastic Ball and EOS data as a function of beam energy for Au+Au.

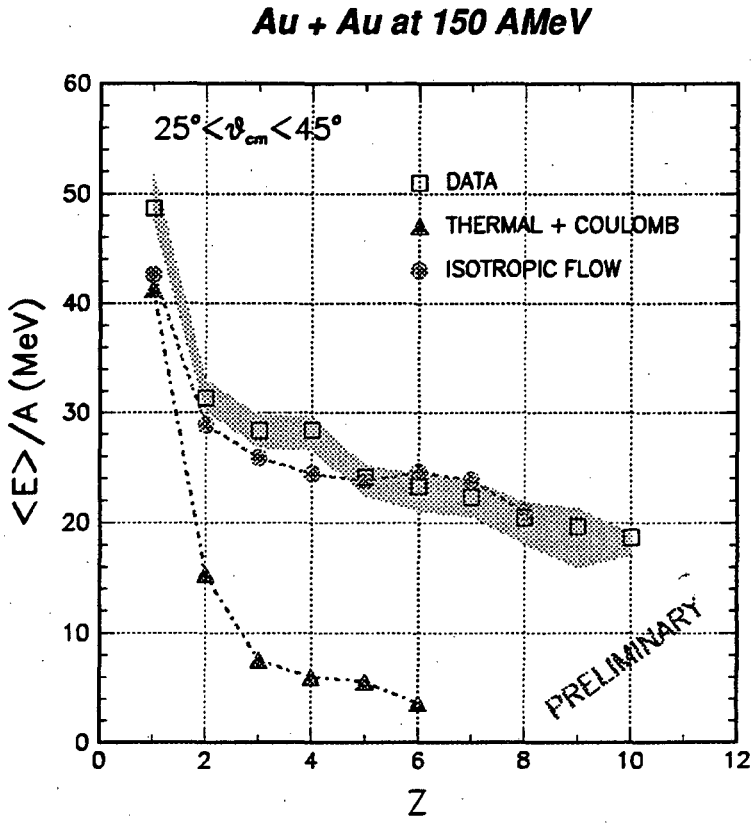

Figure 7. Mean energy per nucleon as a function of fragment charge for Au+Au at 150 MeV per nucleon. The open squares show the FOPI data, the triangles the results from a thermal model, and the circles the expectation for isotropic flow.

it should be expected that this is radial flow, predicted a long time ago.[41] It should be seen at all impact parameters and it should agree well with model calculations[42] that reproduce the directed flow since it is generated by the same mechanism.

Higher Energies

The energy dependence of the flow and the scaling behavior[33] suggest that there will be a large amount of flow at energies higher than one or two GeV per nucleon. With measurements at AGS energies between two and ten GeV per nucleon with the EOS experiment[43] it will be possible to extend the range towards higher density. This is very important since there are new studies suggesting that the density reached at top SIS/Bevalac energies might be lower than expected up to now.[44] Flow at the highest AGS energy has been observed recently.[45]

The energy frontier has moved to the AGS and to CERN. An excellent overview of the physics and the experimental program can be found in topical reviews.[46] At the higher energies the most important goal is to discover and to investigate the Quark-Gluon plasma, a new phase of nuclear matter predicted by lattice-QCD calculations. Of course if one wants to study a new phase it is important to know the properties of the phase from which such a transition is to occur. Thus the much broader goal of AGS and CERN physics is to understand the properties of hot and dense hadronic matter. At higher energies the nature of the nucleon-nucleon interactions changes, resonance production becomes abundant and the influence of the mean field less important. At very high energies string models are generally used to describe the basic interactions. But there are striking similarities as well. As in intermediate energy collisions geometry determines the multiplicity and transverse energy distributions and at the AGS and at CERN we find a very high degree of stopping,[45, 47] indicative of high energy and high baryon density. As in the early days of the Bevalac research only light ions were available initially and so far hadronic effects generally have been sufficient to explain the data. At the AGS we have seen the first results from experiments with Au beams and at CERN the first Pb beams will be available end of 1994. It will be interesting to see if the larger volume will lead to qualitative changes in the results. Also it will be very important to see more realistic models developed that relate the experimental observables to the properties of nuclear matter. Superposition models alone are not sufficient for this task.

SUMMARY

In the intermediate energy range we have seen a great variety of new experimental data. Systematic studies of collective effects, particle production and correlations, sub-threshold production, composite fragment production and correlations, rapidity distributions, multifragmentation, and di-lepton production[48] have been performed during the last years. Individually most of those data have been compared to dynamical models and their sensitivity to static and dynamic properties of nuclear matter have been tested and established. Often the uncertainties in the model predictions are larger than the sensitivity of the experimental observables to the nuclear matter properties. However, the large body of diverse experimental results gives us the chance to test the ability of the models to describe all the data for a given system at a given energy. Only as a result of such a comprehensive comparison will it be

possible to determine the properties of nuclear matter at high density and temperature. Mapping the equation of state in this way over a large range of energies[49] does not depend on the concept of a quadratic form and one parameter, the compression modulus κ, but it will leave open the possibility to find new effects and processes[8] that manifest themselves in the shape of the equation of state.

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TECHNICAL INFORMATION DEPARTMENT
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