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QUO VADIS, BEVALAC PHYSICS

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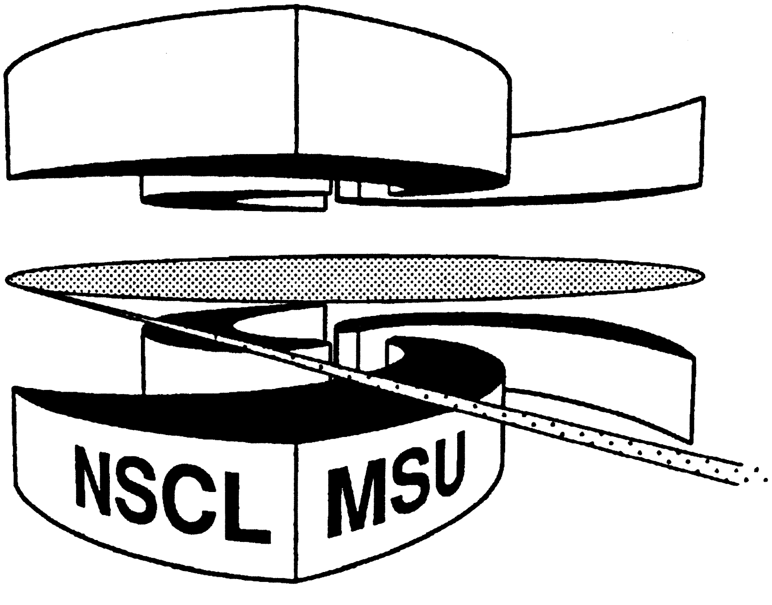
Summary talk,
9th High Energy Heavy Ion Study



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QUO VADIS, BEVALAC PHYSICS ?

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ABSTRACT

The current status of relativistic heavy ion science is reviewed.

1. Introduction

On Saturday, February 21, 1993, the BEVATRON was shut down permanently. This ended two decades of research on relativistic heavy ion physics, which had begun in 1974 when the SUPERHILAC was converted into an injector for the BEVATRON, thus creating the BEVALAC. From the beginning, heavy ion research at the BEVALAC has been an international effort with scientists from the GSI forming the most important collaboration from abroad. One of the results of this collaboration has been the ongoing series of *High Energy Heavy Ion Study* conferences, a series of which the present one is the 9th edition. These conferences were alternatively held at the GSI and at LBL. With the retirement of the BEVALAC, it may well be that this format has come to an end as well. And since this is the last talk of what could be the last *High Energy Heavy Ion Study*, a critical summary of where we are and where we are going with the field of relativistic heavy ion science is in order.

In the following I have attempted to give an account of the most important developments in physics, both experimental and theoretical, resulting from the research effort at the BEVALAC. This account is not so much meant as a review, but rather as a personal perspective. I am also attempting to include the description or at least mentioning of important outstanding problems which have to be addressed in the future. And finally, I try to point out directions into which BEVALAC physics might go, and where this research could be carried out.

Since this present manuscript is not meant to be a comprehensive review, I should point out where reviews can be found. A short overview of the history of BEVALAC physics has recently been published in Physics Today[1]. Several reviews can be found in Annual Review of Nuclear and Particle Science[2–9], in Physics Reports[10–16], and elsewhere.[17–22]

2. Models of Nuclear Dynamics

The field of nuclear dynamics represents an intersection of quantum mechanics, relativity, field theory, many-body theory, particle physics, fluid-dynamics, and thermodynamics. It is thus unrealistic to expect *one definite theory* which explains all observed phenomena to be derived. Progress has rather been made in small incremental steps, resulting from an iterative interaction between theory an experiment.

A large impetus for the field of relativistic heavy ion physics had come form nuclear hydrodynamics calculations[25] in which nuclei are represented by basically incompressible fluids with their motion governed by fluid-dynamics equations. The postulation of nuclear shock waves as a result of these calculations has resulted in two decades of theoretical arguments and experimental searches with proponents and opponents both declaring victory.[26]

One of the first models to be introduced as a means of describing the experimental results obtained by the Plastic Ball group at the BEVALAC was the "Fireball"[23]. Here it was assumed that thermal and chemical equilibration had taken place in the early stages of the nuclear reaction, and that the population of different particle species and energy distributions were then governed by thermodynamics arguments.

At about the same time the first one-dimensional Time-Dependent-Hartree-Fock calculations were performed for nuclear collisions.[24] Motivated by the success of the nuclear shell model, it was assumed here that heavy ion collisions are dominated by the effects of the one-body interaction of individual nucleons with the nuclear mean field.

An opposite approach was taken by proponents of intra-nuclear cascade[27] calculations, neglecting the interaction with the mean field and assuming dominance of two-body interactions. Thus heavy ion reactions were visualized as a sequence of individual independent two-body collisions.

The one- and two-body approaches were synthesized in the so-called Boltzmann-Uehling-Uhlenbeck theory (BUU, otherwise also known by various acronyms such as VUU, BNL, LV, ...).[28,29,12,14,17,19,15,7,22] This theory solves a Boltzmann-like integral equation for the nucleonic phase space density distribution function by utilizing the test particle method.[30] With it, it was for the first time possible to investigate the interplay between kinetic pressure and mean field compressional effects. One of the motivations for this was to determine the compressibility for nuclear matter

$$\kappa = k_f^2 \left. \frac{\partial^2 E_{\text{bind}}/A}{\partial k_f^2} \right|_{\rho=\rho_0} = 9\rho^2 \left. \frac{\partial^2 E_{\text{bind}}/A}{\partial \rho^2} \right|_{\rho=\rho_0} . \tag{1}$$

This goal, however, proved to be very elusive as theorists began to incorporate more and more realistic interactions including their non-locality or momentum dependence, and relativistic generalizations. (See ref. 20 for a review.) Clearly, much more work is to be done here.

The BUU theory is a theory for the time evolution of the one-body Wigner function of nucleons. It is thus not able to properly include fluctuations in its original formulation. Attempts to improve on this point were directed to include fluctuations into the same formalism.[31]

An alternate way was motivated by using the test particle method in the limit of one test particle per nucleon, resulting in a molecular dynamics-type simulation, QMD[32,16] and QPD.[33] These models were produced in order to describe nuclear fragmentation. At beam energies above E/A $\approx$ 200 MeV this prescription seems to work well. At lower beam energies, however, where there is a maximum in the yield of intermediate mass fragments, QMD does not seem to work as well as desired (see the contributions of G. Peilert, M. Begemann-Blaich, M.B. Tsang, and C. Sangster in this volume). This might be due to an improper dependence of the entropy on the excitation energy in these calculations, resulting from the fact that they basically use classical dynamics as their foundation.

A possible remedy for this may be found along the way of the Fermionic Molecular Dynamics (FMD)[34,21,35] where the many body wave function of the nuclear system is taken as a truncated Slater determinant of Gaussian wave packets representing individual nucleons. At present, the procedure to include nucleon-nucleon collisions is implemented in an ad hoc way, but seems to result in better agreement with data.

A wide array of investigations to improve the present state of modeling nuclear dynamics is underway. While the progress over the last two decades has been very impressive, many fundamental questions remain unanswered. These include the proper inclusion of fluctuations, of three- and more-nucleon interactions, of true quantum effects, of consistent inclusion of mesonic degrees of freedom and retardation effects, of consistency between mean field and two-body interaction in the models. As more and better experimental data arrive, theoretical models become more and more constrained, and it is possible to falsify some (or even all) of them, replacing them with better ones. Some of the data driving this development will be examined in the following sections.

3. Particle Production

The only observables from heavy ion collisions which are accessible to experiment are the asymptotic momentum states of outgoing particles. These particles can roughly be divided into two groups: Primary particles (protons, neutrons, deuterons, tritons, helium nuclei, and heavier fragments such as intermediate mass fragments, evaporation residues, or target and projectile like fragments) and secondary particles (pions and other non-strange mesons, kaons and other strange mesons, strange baryons, anti-protons and other antiparticles, photons, di-lepton pairs, ...).

The primary category consists of particles made up of neutrons and protons, building blocks already present in the two colliding nuclei. The minimum energy needed to emit these particles is therefore only of the order of the difference in the binding energies between the emitting nuclear system and the ejectile, $\Delta E/A \leq 8$ MeV.

The particles in the secondary category are all created during the heavy ion collision. The minimum energy needed for their creation is their rest mass, M_0, in cases where the production of a single meson is not forbidden by conservation laws (e.g.: pion). In cases where particles can only be produced in pairs, the energy cost is even higher. For example, to produce a K^+, the minimum energy needed is

$$E_{\text{min}} = M_0(K^+) + M_0(\Lambda) - M_0(p) \tag{2}$$

in the center of mass of the emitting system. Therefore the production of these particles can be a signature for a very energetic event. This is even true for the production of photons or di-lepton pairs, where one can select high photon energies or large values of the invariant mass, $M_{\text{inv}}^2 = (\hat{P}_1 + \hat{P}_2)^2$, of the pair.

3.1. Medium Effects and the Nuclear Equation of State

At beam energies above nucleon-nucleon threshold the production of secondary particles is dominated by production from individual two-nucleon collisions. One can ask which medium effects play a role in modifying the elementary production probabilities and lead to observable consequences distinguishing particle production in the nuclear medium from an incoherent superposition of nucleon-nucleon collisions.

The most elementary of these effects is the motion of nucleons inside ground state nuclei due to the effects of the Pauli exclusion principle, the so-called Fermi motion. The maximum relative momentum between two nucleons from two different nuclei is then not just the beam momentum, p_b, but $p_b + 2p_{\text{f}}$, where $p_{\text{f}} \approx 250$ MeV/c is the Fermi-momentum. However, in the process of particle production, the outgoing nucleons have to scatter into unoccupied regions of phase space, another consequence of the exclusion principle.[36]

Transport calculations show that it is too simple-minded, however, to represent the two colliding nuclei as two (possibly overlapping) Fermi spheres in momentum space. The acceleration of the two approaching nuclei towards each other as their surfaces touch leads to a depletion of phase space density in the central region and opens up the so-called Fermi-hole.[37] This was shown to cause the preferred emission of high energy particles during the early states of the heavy ion reaction and thus makes particle production a sensitive probe of the high-compression phase.

Other medium effects playing important roles are the rescattering and reabsorption of produced particles[38] as well a medium-modifications to the elementary scattering process. All of these medium effects make subthreshold particle production an important testing ground for models of nuclear collisions and fundamental probes of nuclear dynamics. (See the contributions of H. Gutbrod, S. Bass, C. Muentz and P. Senger in this volume).

A very important idea in the development of relativistic heavy ion physics was the attempt to determine the nuclear compressibility from pion multiplicities.[39] The underlying assumption is that the energy spent to compress nuclear matter is not available for particle production. By comparing the observed pion multiplicities to intranuclear cascade calculations without compressional effects, it was thus hoped to extract the nuclear compressibility. Shortly thereafter it was shown, however, that this initial attempt was too simple-minded, and that better cascade calculations were indeed able to reproduce the observed multiplicities.[40]

However, this initial idea remained a powerful driving force for the development of nuclear transport theories sketched above. For example, the first BUU transport theory paper[28] studied the dependence of the calculated pion multiplicity on the stiffness of the nuclear equation of state by selfconsistently including mean field compressional effects into the calculation.

In a refined version of this idea one investigates particle production around the threshold region, where the elementary production cross section is a very steep function of the available center-of-mass energy, thus yielding a more sensitive probe. However, then the use of pions as a probe is not a viable option, because the beam energy region of E/A $\approx$ 200 MeV is not expected to result in high compressions. A better probe thus seems to be the threshold production of kaons (see the contributions of E. Grosse and G. Li in this volume).

However, I remain somewhat skeptical as far as the chances for success are concerned. First, one has to realize that a change in the numerical value of the nuclear compressibility does not entail a corresponding proportional change in compressional energy. Rather what happens in transport calculations is that the maximum density reached adjusts to largely compensate for the change in compressibility, leading to roughly the same fraction of the total available energy being stored in compression.

Another effect that further complicates this simple picture is that at higher beam energies the population of resonances increases drastically. This leads to the exciting new possibility of (primarily Δ-) resonance matter (see the contribution of R. Simon). However, the resonance matter introduces also new uncertainties into the calculations for particle production, because, for example, around E/A = 1 to 2 GeV beam energy the dominant contribution to kaon production comes from reactions like

$$N + \Delta \rightarrow K + X \qquad \text{and} \qquad \Delta + \Delta \rightarrow K + X. \tag{3}$$

The calculation of the kaon production process requires then knowledge of the above elementary cross sections, which cannot be independently extracted from experiment, and whose medium modifications are unknown.

3.2. Subthreshold Particle Production

Far below threshold, several nucleons have to pool their energies to provide for the particle production. This can be accomplished by several subsequent individual nucleon-nucleon collisions in the spirit of the Fermi acceleration, energy storage through resonance excitations (see above), or by a collective emission of the particle as first suggested by Heisenberg[41,42]. A recent BEVALAC study to find traces of this effect (see Fig. 1) was conducted by dividing the pion production cross section for heavy systems by that for light systems[43]. However, down to a beam energy of 183

MeV per nucleon, no collective pion production component was visible in the data - in agreement with the BUU calculations assuming non-collective production. In fact, as of today no experimental studies on pion production in the subthreshold region have conclusively discovered any signatures of a collective production.[3,6]

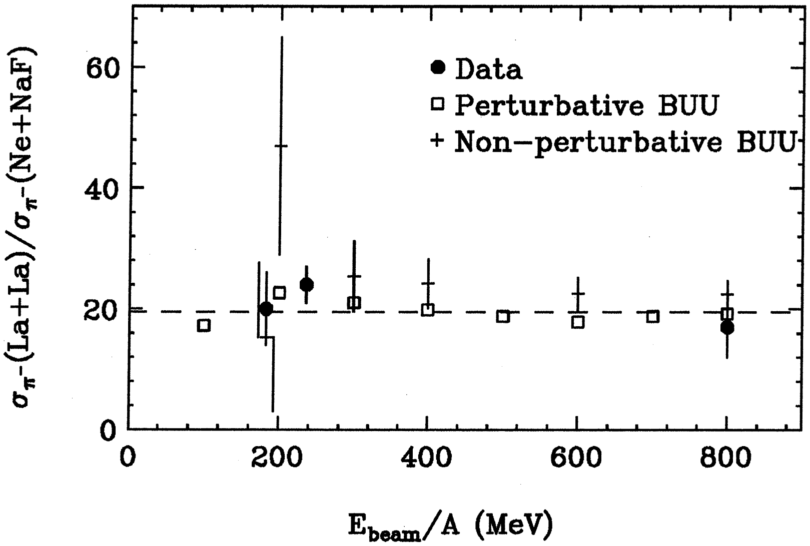

Fig. 1: Comparison between pion yield ratios from experiment (filled circles) and from two BUU calculations (perturbative - open squares; non-perturbative - crosses) (from ref. 43).

There are several open problems which warrant further study of subthreshold particle production. First, higher statistics studies of the kind described here have to be extended to lower beam energies to see if the heavy/light pion production ratio changes. Another way to address possible collective production is the impact parameter dependence of pion production by using 4π detectors as impact parameter filters. Similar studies can of course be conducted for the subthreshold production of other particles as well.

A further problem is the so-called 'slope anomaly' in pion production data. The energy spectra of produced secondary particles show a 'thermal' spectrum with an exponential fall-off conventionally parametrized via a constant T_0, called the 'temperature'. Naively, one would expect this temperature constant to be a monotonic (possibly even linear) function of the beam energy, with T_0 approaching 0 for the beam energy approaching 0.

This, however, does not seem to be the case. Instead, what is observed is a certain minimum apparent temperature in the pion spectra, $T_0(E_b) > 10$ MeV for all beam energies.[3,44] This present puzzle may have an intimate connection to a similar discrepancy between nuclear fragment energy spectra (which show a similar minimum 'temperature') and the nuclear temperature parameter as extracted from the measurement of population ratios of excited states relative to the ground state.[45] Interestingly enough this puzzle does not seem to exist for the slope parameters in high energy photon production.[15]

3.3. Electromagnetic Probes

With the current amount of activity devoted to studying high energy photon and di-lepton pair production from heavy ion collisions (see the contributions by W.K. Wilson, R.J. Porter, K. Haglin, C.M. Ko, and H. Specht), it seems appropriate to devote a separate section to these probes in this summary.

Electromagnetic probes derive the interest in them from the fact that they practically do not interact with the nuclear medium once they have been produced. They thus represent relatively clean probes of the hot and dense phase of the heavy ion collision.

From the study of high energy gamma production we have learned that (i) high energy photons are primarily produced in individual nucleon-nucleon collisions; (ii) meson-exchange currents play an important or even dominant role; (iii) high energy photons carry important information on the heavy ion reaction dynamics. Unfortunately, at higher beam energies, the decay of neutral pions into two gammas provides severe background problems. There may, however, be another source of high energy photons,[46] the decay $\Delta \to N + \gamma$, visible in the data (see R. Simon's contribution), shedding light on the exciting Delta-matter.

From di-lepton pair measurements we expect to learn about the pion-pion interaction in the nuclear medium and indirectly about the pion dispersion relation in nuclear matter. We can study the Dalitz-decay of mesons and baryons, investigate electromagnetic form factors, and learn about possible shifts of the masses and widths in the medium, with a possible glimpse at chiral restoration. All of these prospects are very exciting, but the current data do not constrain the models sufficiently. With the construction of the di-lepton spectrometer HADES at the GSI the available statistics for di-lepton pairs should increase by at least three orders of magnitude, however (see W. König's contribution).

4. Two-Particle Correlations

The information that can be extracted experimentally from one-body observables is limited. Fig. 2 illustrates this problem. On the left, we show schematically the expansion of a source in time, where the different shaded ovals are meant to represent snapshots of the source at different time instances. Particles emitted from this source will move on a straight trajectory (for simplicity we neglect the effects of bending magnets in spectrometers) to the detector. This detector can only record the asymptotic momentum state, $|\vec{p}(t \to \infty)\rangle$, of the detected particle. No coordinate space information on the emission point can be generated from this. Thus the measured single particle spectra represent an integration over the entire space-time extension of the emitting source.

The situation is different for correlated two particle observables. The final state interaction between the pair (represented by the oval containing the last directional change in the trajectories of the two particles) modifies their asymptotic momentum states, and due to this correlation, the two-particle final state is not simply the direct product of the single particle states. This correlation can be expressed as

$$\mathcal{C}(\vec{p}_1,\vec{p}_2) = \frac{\langle \vec{p}_1,\vec{p}_2|\vec{p}_1,\vec{p}_2(t\rightarrow\infty)\rangle}{\langle \vec{p}_1|\vec{p}_1(t\rightarrow\infty)\rangle\langle \vec{p}_2|\vec{p}_2(t\rightarrow\infty)\rangle} \tag{4}$$

And, since the interaction between the two particles in general depends on the separation of the two particles, so will the correlation function defined here. We can thus hope to extract information on the space-time extension of the emitting source from coincidence measurements of two (or more) emitted particles.

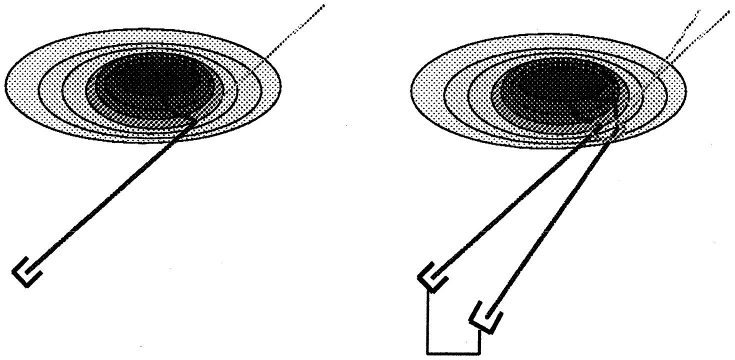

Fig. 2: Left: detection of a single particle emitted from an expanding source; right: simultaneous detection of two particles from the same source.

It has to be stressed that this volume information is essential for all attempts to make inferences about the nuclear equation of state. To obtain this information, it is not enough to perform simple global gaussian source fits to the data. Rather the data (and calculations) should in an ideal case be impact parameter binned. In addition, one has to differentiate between different pair velocities, $\vec{P}$, of the emitted particle pair, because the emission of high energy particles is more localized in time during a heavy ion collision, thus resulting in a smaller effective source 'radius' than that extracted for less energetic particles. Another cut providing very useful information is the distinction between longitudinal ($\vec{q}\,||\,\vec{P}$) and transverse ($\vec{q}\perp\vec{P}$) correlations, where $\vec{q}$ is the relative momentum between the emitted pair (see M. Lisa's contribution). This information can be used to disentangle the contributions of life time effects and coordinate space extension of the source to the extracted effective radius.

The comparison of the results of transport calculations to experimental data has progressed enormously in the beam energy range around the Fermi energy during the last few years.[7,22] However, for relativistic energies this comparison is still in its infancy stage. Here I see a huge potential for future experiments and detailed calculations, providing possible additional narrowing down of the parameter windows for the nuclear equation of state.

As an example for the predictive power of present-day heavy ion transport theories Fig. 3 shows a comparison of data obtained by the DIOGENE collaboration[47] to the calculations for opposite sign pion correlations

$$R_{\pi^+\pi^-} = \frac{\sigma_2(\pi^+,\pi^-)}{\sigma_1(\pi^+)\sigma_1(\pi^-)} \tag{5}$$

as a function of the invariant mass of the pair. From this figure, we can clearly see an enhancement of the correlation function close to $M_{\rm inv} = 2m_\pi$ for the p+Pb case, whereas it is not present in the p+C case. In the calculations this is due to the effects of pion and delta resonance re-scattering and re-absorption, and the difference is caused by the fact the $R_{\rm Pb} \gg \lambda_\pi \approx R_{\rm C}$, where λ_π represents the mean free path of pionic excitations in nuclear matter.

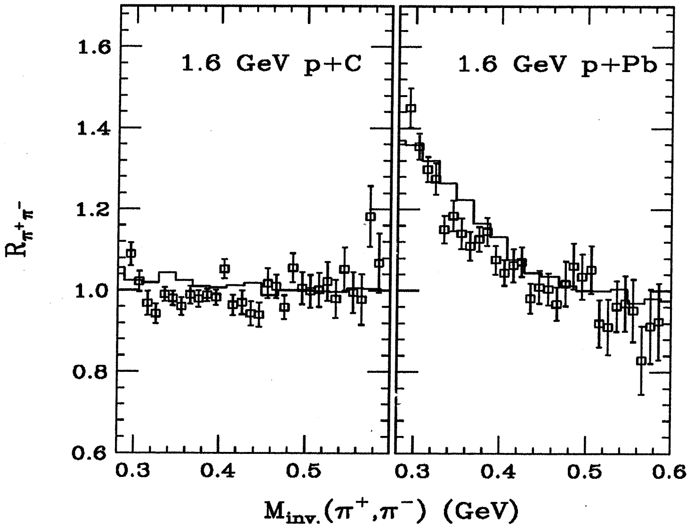

Fig. 3: Two-pion ($\pi^+\pi^-$) correlation function for 1.6 GeV proton induced reactions on C and Pb targets. The histograms represent the calculations, and the circles show the data of the DIOGENE collaboration.[47]

5. Collective Motion

Phenomena of collective motion of nucleons resulting from nuclear collisions are one of the most fascinating objects of study in relativistic heavy ion collisions, because they offer glimpses at true many-body effects not present in simple superpositions of individual two-body collisions. Early effects postulated were nuclear 'shock waves'[25,26] and 'blast waves'.[48]

The important effect of sidewards deflection in the reaction plane ('flow') was discovered by the Plastic Ball group at the BEVALAC.[49] Furthermore, a preferred emission out of the reaction plane around midrapidity was found by the Streamer Chamber group.[50] In addition, radial outward flow has been theoretically considered[51,52] and observed in the data. This radial flow phenomenon may at lower energies even lead to the transient formation of hollow structures, bubbles, toroids,[53] or sheets.[54] (See also the contribution of E. Norbeck).

Again, the investigation of nuclear collective flow has largely been driven by the motivation to determine the nuclear compressibility and in turn has driven the development of transport theories (see the contributions of N. Herrmann, F. Rami, Y. Leifels, S. Bass, P. Senger, and H. Loehner).

Another exciting development are the new EoS TPC data (see the contribution of D. Keane) showing a non-viscous hydrodynamic scaling, a constant scale invariant flow of ≈ 0.35, for beam energies between E/A = 200 and 1200 MeV (see D. Keane's contribution).

At lower energies, E/A $\approx$ 50 to 100 MeV, the repulsive nuclear collective flow is balanced by the attractive nuclear surface interaction. The beam energy at which this happens was called the 'balance energy'.[55] It was shown that the projectile and target mass dependence of this quantity enables us to estimate the density dependent medium corrections of the nucleon-nucleon scattering cross section, with the best value suggesting a $\approx 20\%$ reduction as compared to the free value at nuclear matter density.[56,57] (See G. Westfall's contribution).

There are several challenges in this area remaining to be solved. Apart from a further determination of the parameters of the nuclear equation of state discussed above, we would like to see an experimental investigation into the postulated non-compact shapes; a continuation of the flow studies to higher energies to see how far upward the observed hydrodynamic scaling can be extended and to determine what the energy dependence of the different contributions (mean field compression and kinetic pressure) to the collective flow observable are; and finally a thorough investigation of the beam energy range between 50 and 200 MeV to determine at what energy hydrodynamic scaling breaks down and results in the disappearance of nuclear flow, an effect not predicted by this simple scaling picture.

6. Multifragmentation

The disintegration of excited nuclei into several smaller nuclei of light to intermediate mass is probably the most serious challenge to today's theoretical understanding of the nuclear many-body problem – as already discussed above.

Several 4π multiparticle detection systems are now delivering data of outstanding quality and statistics. The main objective is, in my opinion, to try to investigate the possibility of a first or second order phase transition of nuclear matter in these fragmentation events. Early studies on high-energy proton induced fragmentation reactions seemed to indicate the possible presence of this effect, but were not very useful because they were inclusive data, i.e. integrated over impact parameter and energy deposited.[58] Now exclusive experiments for reverse kinematics[59] and mass symmetric systems[60] have begun to map out the excitation function for the intermediate mass fragment production and seem to consistently indicate a critical excitation energy per nucleon of about 8 MeV (see also contributions by M.B. Tsang, C. Sangster, M. Begemann-Blaich, G. Wozniak, and V. Lindenstruth).

New studies conducted with reverse kinematics and utilizing the EoS TPC have now confirmed the predicted[61] impact parameter dependence of the fragment production cross section. Much more important, for the same data set a moment analysis of fragment mass distribution[62,61] was conducted in an event-by-event manner. This enables one to determine the critical exponents of nuclear matter at the critical point (see contribution by A. Hirsch).

We have only begun to explore the vast possibilities of investigations into the nature of the phase transition. From the experience gained here there may also be a possible cross fertilization of methods with the future search for the quark-gluon plasma phase transition at much higher excitation energies. Possibly the most important contribution to physics in general is to be made by exploring how finite size effects wash out signatures of phase transitions in very small systems of only on the order of 100 constituents.

7. Summary

In the space allocated it was impossible for me to provide an adequate summary of the field, or even to mention (let alone discuss) everybody's contributions to this workshop. The whole area of radioactive secondary beam physics, for example, was not covered at all in my overview. However, what I hoped to convey is the multitude of exciting new results and future directions in relativistic heavy ion physics.

8. Quo Vadis, BEVALAC Physics?

On Saturday, February 21, 1993, the BEVALAC was retired. But the science of relativistic heavy ion physics has not died with it.

Fittingly, the bulk of the investigations started here will be carried on by the SIS accelerator at the GSI. The continuation to higher energies will be provided by the AGS accelerator at Brookhaven National Laboratory. At the low end of the BEVALAC's beam energy range, the NSCL at Michigan State University is currently operating the K1200 accelerator and is planning for an upgrade to be able to accelerate beams over the entire mass range up to energies of E/A = 200 MeV. Other accelerators around the world are also contributing valuable parts to the ongoing investigations into relativistic heavy ion science.

In the mean time, the field of relativistic heavy ion physics has also branched out to higher energies in the quest to discover positive evidence for the existence of the the quark-gluon-plasma. To a large degree this effort was and is driven by scientists having worked at the BEVALAC at one time or another during their career. Many of the ideas generated by the interaction of theorists and BEVALAC-experimenters have been propagated and extended into the subfield of ultrarelativistic heavy ion physics.

All of these ongoing efforts convince the observer that the shutdown of the BEVALAC does not constitute the end of relativistic heavy ion science. It is alive and well. I thus conclude with the words of Winston Churchill

> *"This is not the end.*
> *It is not even the beginning of the end.*
> *But it is, perhaps, the end of the beginning."*

9. References

[1] S. Das Gupta and G.D. Westfall, Physics Today **46**(5), 34 (1993).
[2] D. Boal, Annu. Rev. Nucl. Part. Sci. **37**, 1 (1987).
[3] P. Braun-Munzinger and J. Stachel, Annu. Rev. Nucl. Part. Sci. **37**, 97 (1987).
[4] W.G. Lynch, Annu. Rev. Nucl. Part. Sci. **37**, 493 (1987).
[5] H. Nifenecker and J.A. Pinston, Annu. Rev. Nucl. Part. Sci. **40**, 113 (1990).
[6] U. Mosel, Annu. Rev. Nucl. Part. Sci. **41**, 29 (1991).
[7] W. Bauer et al., Annu. Rev. Nucl. Part. Sci. **42**, 77 (1992).
[8] J. Stachel and G.R. Young, Annu. Rev. Nucl. Part. Sci. **42**, 537 (1992).
[9] L. Moretto and G.J. Wozniak, Annu. Rev. Nucl. Part. Sci. **43**, 379 (1993).
[10] L.P. Czernai and J.I. Kapusta, Phys. Rep. **131**, 223 (1986).
[11] R. Stock, Phys. Rep. **135**, 259 (1986).
[12] H. Stöcker and W. Greiner, Phys. Rep. **137**, 277 (1986).
[13] B. Schürmann et al., Phys. Rep. **147**, 1 (1987).
[14] G.F. Bertsch and S. Das Gupta, Phys. Rep. **160**, 189 (1988).
[15] W. Cassing et al., Phys. Rep. **188**, 363 (1990).
[16] J. Aichelin, Phys. Rep. **202**, 233 (1991).
[17] P. Schuck et al., Prog. Part. Nucl. Phys. **22**, 181 (1989).
[18] H. Gutbrod et al., Rep. Prog. Phys. **52**, 267 (1989).
[19] W. Cassing and U. Mosel, Prog. Part. Nucl. Phys. **25**, 235 (1990).
[20] S.J. Wang et al., Ann. Phys. (N.Y.) **209**, 251 (1991).
[21] A. Ono et al., Prog. of Theoret. Phys. **87**, 1185 (1992).
[22] W. Bauer, Prog. Part. Nucl. Phys. **30**, 45 (1993).
[23] G.D. Westfall et al., Phys. Rev. Lett. **37**, 1202 (1976).
[24] P. Bonche et al., Phys. Rev. C **13**, 1226 (1976).
[25] W. Scheid et al., Phys. Rev. Lett. **32**, 741 (1974).
[26] "The Nuclear Equation of State", ed.: W. Greiner and H. Stöcker, NATO ASI Series B **216A** (Plenum, New York, 1989).
[27] J. Cugnon et al., Nucl. Phys. **A352**, 505 (1981).
[28] G.F. Bertsch et al., Phys. Rev. C **29**, 673 (1984).
[29] J. Kruse et al., Phys. Rev. Lett. **54**, 289 (1985).
[30] C.-Y. Wong, Phys. Rev. C **25**, 1460 (1982).
[31] W. Bauer et al., Phys. Rev. Lett. **58**, 863 (1987).

[32] J. Aichelin and H. Stöcker, Phys. Lett. **B176**, 14 (1986).
[33] D.H. Boal and J.N. Glosli, Phys. Rev. C **38**, 2621 (1988).
[34] H. Feldmeier, Nucl. Phys. **A515**, 147 (1990).
[35] A. Ono et al., Phys. Rev. Lett. **68**, 2898 (1992).
[36] G.F. Bertsch, Phys. Rev. C **77**, 713 (1977).
[37] W. Bauer et al., Phys. Rev. C **34**, 2127 (1986).
[38] B.A. Li and W. Bauer, Phys. Rev. C **44**, 450 (1991).
[39] R. Stock et al., Phys. Rev. Lett. **49**, 1236 (1982).
[40] Y. Kitazoe et al., Phys. Lett. **B166**, 35 (1986).
[41] W. Heisenberg, Z. Phys. **126**, 569 (1949).
[42] D. Vasak et al., J. Phys. G **11**, 1309 (1985).
[43] J. Miller et al., Phys. Lett. **314B**, 7 (1993).
[44] T. Suzuki, Nucl. Phys. A**538**, 113c (1992).
[45] W. Bauer, to be published in the proceedings of the Les Houches Winter School on Fragmentation Phenomena.
[46] W. Bauer and G.F. Bertsch, Phys. Lett. **229B**, 16 (1989).
[47] J. Pluta et al., Nucl. Phys. **A562**, 365 (1993).
[48] P.J. Siemens and J.O. Rasmussen, Phys. Rev. Lett. **42**, 880 (1975).
[49] H.A. Gustafsson et al., Phys. Rev. Lett. **52**, 1590 (1984).
[50] P. Danielewicz et al., Phys. Rev. C **38**, 120 (1988).
[51] P. Danielewicz and Q. Pan, Phys. Rev. C **46**, 2002 (1992).
[52] W. Bauer et al., Phys. Rev. C **47**, R1838 (1993).
[53] W. Bauer et al., Phys. Rev. Lett. **69**, 1888 (1992).
[54] L. Moretto et al., Phys. Rev. Lett. **69**, 1884 (1992).
[55] C.A. Ogilvie et al., Phys. Rev. C **42**, R10 (1990).
[56] G.D. Westfall et al., Phys. Rev. Lett. **71**, 1986 (1993).
[57] D. Klakow et al., Phys. Rev. C **48**, 1982 (1993).
[58] A.S. Hirsch et al., Phys. Rev. C **29**, 508 (1984).
[59] C.A. Ogilvie et al., Phys. Rev. Lett. **67**, 1214 (1991).
[60] T. Li et al., Phys. Rev. Lett. **70**, 1924 (1993).
[61] W. Bauer, Phys. Rev. C **38**, 1927 (1988).
[62] X. Campi, J. Phys. **A19**, L917 (1986).