

Lawrence Berkeley National Laboratory

Recent Work

Title

Flow and Multifragmentation in Nuclear Collisions at Intermediate Energies

Permalink

<https://escholarship.org/uc/item/535846vx>

Authors

Ritter, Hans G.
Albergo, S.
Bieser, F.
et al.

Publication Date

1994-06-01

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal 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 its 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, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-36105
UC-414

To be published in the Proceedings of the
Fifth International Conference on Nucleus Nucleus Collisions
Taormina, Italy, 30 May-4 June 1994,

**Flow and Multifragmentation in Nuclear Collisions at Intermediate
Energies**

H.G. Ritter
Lawrence Berkeley Laboratory
University of California, Berkeley, CA 94720

and

The EOS Collaboration

June 1994

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of Nuclear Physics of the U.S. Department of Energy under Contracts DE-AC03-76SF00098, DE-FG02-89ER40531, DE-FG02-88ER40408, DE-FG02-88ER40412, DE-FG05-88ER40437, and by the National Science Foundation under Grant PHY-9123301.

Flow and Multifragmentation in Nuclear Collisions at Intermediate Energies

H. G. Ritter^a, S. Albergo^f, F. Bieser^a, F. P. Brady^d, Z. Caccia^f, D. A. Cebra^d, A. D. Chacon^e, J. L. Chance^d, Y. Choi^c, S. Costa^f, J. B. Elliott^c, M. L. Gilkes^c, J. A. Hauger^c, A. S. Hirsch^c, E. L. Hjort^c, A. Insolia^f, M. Justice^b, D. Keane^b, J. Kintner^d, V. Lindenstruth^g, M. A. Lisa^a, U. Lynen^g, H. S. Matis^a, M. McMahan^a, C. McParland^a, W. F. J. Mueller^g, D. L. Olson^a, M. D. Partlan^d, N. T. Porile^c, R. Potenza^f, G. Rai^a, J. Rasmussen^a, J. Romanski^f, J. L. Romero^d, G. V. Russo^f, H. Sann^g, R. P. Scharenberg^c, A. Scott^b, Y. Shao^b, B. K. Srivastava^c, T. J. M. Symons^a, M. L. Tincknell^c, C. Tuvè^f, S. Wang^b, P. G. Warren^c, H. H. Wieman^a, K. L. Wolf^e

EOS Collaboration

^aLawrence Berkeley Laboratory, Berkeley, California 94720

^bKent State University, Kent, Ohio 44242

^cPurdue University, West Lafayette, Indiana 47907

^dUniversity of California, Davis, California 95616

^eTexas A&M University, College Station, Texas 77843

^fUniversità di Catania and INFN-Sezione di Catania, 95129 Catania, Italy

^gGesellschaft für Schwerionenforschung, D-64220 Darmstadt 11, Germany

Energy spectra of hydrogen and helium isotopes emitted in Au+Au collisions at 0.25, 0.40, 0.60, 0.80, 1.0, and 1.15A GeV have been measured. A systematic study of the shapes of the spectra reveals a significant non-thermal component consistent with collective radial flow. The strength of this component is evaluated as a function of bombarding energy. Comparisons of the flow signal to predictions of QMD and BUU models are made. Using reverse kinematics, the breakup of gold nuclei has been studied in Au+C reactions at 1.0A GeV. The moments of the resulting charged fragment distribution provide evidence that nuclear matter possesses a critical point observable in finite nuclei. Values for the critical exponents γ , β , and τ have been determined. These values are close to those for liquid-gas systems and different from those for 3D percolation.

1. INTRODUCTION

The study of nuclear collisions at Bevalac/SIS energies focuses on the production and the decay of the hot and dense source formed for a very short time span. From the study of flow effects, particle production, and fragment formation we try to infer the static and dynamic properties of nuclear matter [1]. Of particular interest are the composite fragments. Due to their large mass they are a much better messenger of flow effects [2,3] than the protons. The interest in fragments, however, is not limited to the hot and dense

phase of the collision. Over the last years fragment formation and its time scale and the breakup of nuclear matter in many intermediate mass fragments, multifragmentation, has been the subject of intense investigations at many different energies. More than a decade ago the observation of a power law distribution in the yield of intermediate mass fragments produced in high energy proton-nucleus collisions led to the suggestion that nuclear multifragmentation might be a critical phenomenon [4]. Since that time, much progress has been made in understanding how critical behavior could manifest itself in such a small system. In particular, Campi [5] and Bauer [6] suggested that the moments of the fragment distribution should exhibit features characteristic of critical phenomena if indeed intermediate mass fragments were produced in a system near its critical point. Recent experimental results from the ALADIN collaboration [7] have shown that existing models based on nuclear physics do not describe multifragmentation data as well as a simple percolation-based model, which is known to contain critical behavior [8].

The EOS collaboration has recently completed a systematic measurement of heavy ion collisions at Bevalac energies that allows us to investigate both flow effects and multifragmentation, under optimal conditions. Radial flow is studied with central Au+Au collisions, the system used in other experiments [3,9]. Large solid angle coverage, good particle identification for the hydrogen and helium isotopes, and zero transverse momentum threshold allow us to study the spectra of the emitted particles as a function of bombarding energy and emission angle without stringent cuts on event centrality. Multifragmentation is studied in reverse kinematics with a 1.0A GeV Au beam on a C target. In this configuration the energy deposited in the Au nucleus can vary considerably. At large impact parameters the Au nucleus is only lightly excited whereas at small impact parameters we can observe complete vaporization. However, the overlap volume remains small enough so that compression and subsequent flow effects are not complicating the decay dynamics [9]. In the reverse kinematics setup the EOS detector can identify the charges of all fragments with very high efficiency. This gives us the possibility to perform a complete experiment in charge space.

2. THE EOS EXPERIMENT

The data were taken with the EOS experiment at Lawrence Berkeley Laboratory using Au beams from the Bevalac with bombarding energies ranging from 0.25 to 1.15A GeV. Fig. 1 shows a schematic view of the detector system. Charged particles were identified using a time projection chamber (TPC) [10] for $1 \leq Z \leq 6$, a time-of-flight wall (TOF) for $7 \leq Z \leq 10$, and a multiple sampling ionization chamber (MUSIC) [11] for $11 \leq Z \leq Z_{\text{beam}}$. The Neutron Spectrometer (MUFFINS) [12] was not used for the analysis described here. The TPC has good particle identification capability and good momentum resolution. Simulations show that tracks from the projectile source and from midrapidity can be reconstructed with very high efficiency, while the efficiency for reconstructing tracks from the target source is low. The MUSIC detector has charge resolution $\sigma = 0.2e$ and was positioned such that $\sim 95\%$ of all fragments $11 \leq Z \leq Z_{\text{beam}}$ fell within its acceptance. The TOF had a comparable acceptance. For the Au + C reaction at 1.0A GeV the total reconstructed charge, Z_{sum} , peaks at 79 with a full width at half maximum of 6.

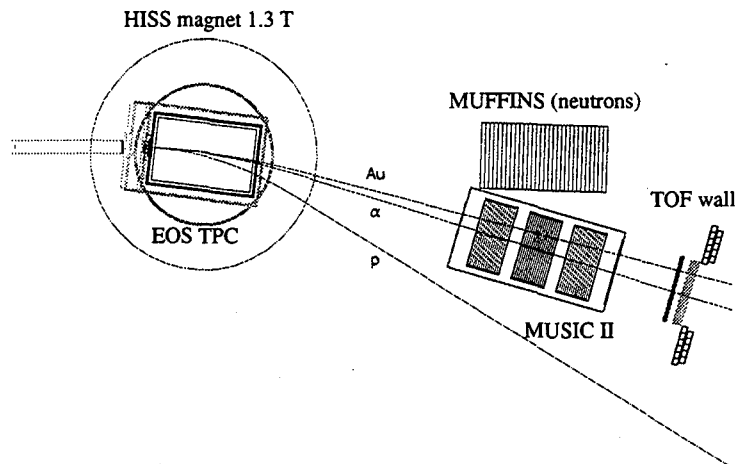


Figure 1. The EOS experimental setup.

3. RADIAL FLOW

The recent report of a large new component of collective flow [3] has stimulated interest in the spectral distribution of the light fragments produced in Au+Au collisions. The energy distribution in the center of mass for particles emitted from a thermally-equilibrated, radially-expanding source, characterized by a temperature T and a radial flow velocity β , is given by the functional form [13]

$$\frac{dN}{dE d\Omega} \sim p e^{-\gamma E/T} \left\{ \frac{\sinh \alpha}{\alpha} (\gamma E + T) - T \cosh \alpha \right\} \quad (1)$$

where E and p are the total energy and momentum of the particle in the center of mass, $\gamma = (1 - \beta^2)^{-1/2}$, and $\alpha = \gamma \beta p / T$. The concept of an equilibrated source is quite simplistic, but it provides a useful way to parameterize the data and identify important components in the decay of the excited system. We have extracted the parameters T and β by fitting Eq. 1 to the energy spectra measured at $\theta_{cm} = 90^\circ \pm 15^\circ$, using a χ^2/ν (chi-squared per degree of freedom) minimization technique.

Fig. 2 shows kinetic energy spectra for protons, deuterons, tritons, ^3He , and α particles for the reaction Au+Au at 1.0A GeV. The data (circles) are from the most central events as selected by the charged particle multiplicity (M5 in the Plastic Ball group convention [14]). Also shown are fits with Eq. 1. Solid lines indicate a simultaneous fit to all spectra, excluding the protons, by varying β and T . A good overall fit is obtained, with a χ^2/ν on the order of unity. Dashed lines represent the fits for a purely thermal scenario, that is $\beta = 0$. The spectra are not as well reproduced, especially for the heavier fragments. Such behavior is observed at all bombarding energies.

When the spectrum for a given fragment type ($d, t, ^3\text{He}, \alpha$) is fit individually, the extracted temperature and flow values are consistent with the ones obtained with the simultaneous fit of all particle types. However, fit parameters for the protons deviate from the parameters for the heavier fragments. At all bombarding energies, proton spectra consistently yield a lower temperature and a greater flow parameter. This can be qualitatively

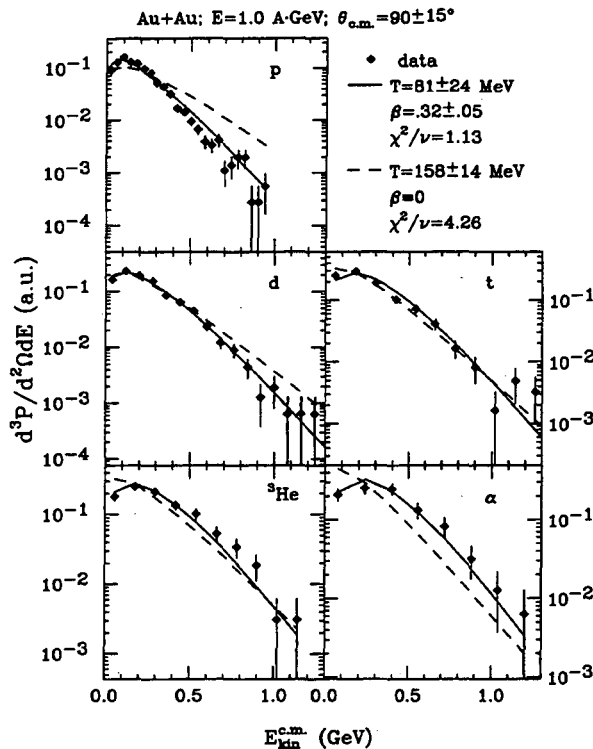


Figure 2. Energy spectra for light fragments emitted into $\theta_{cm} = 90^\circ \pm 15^\circ$. Fits with a radially-expanding thermal source (solid lines), and a purely thermal source (dashed lines) are also shown.

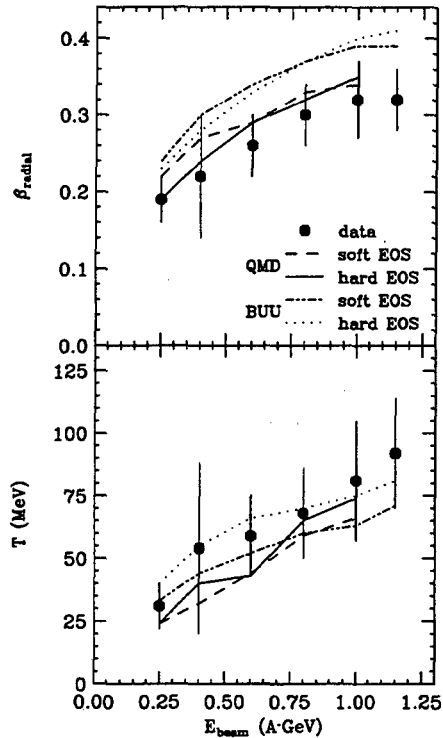


Figure 3. Energy dependence of the temperature and radial flow parameters for the most central Au+Au collisions for the data and for QMD and BUU calculations.

understood [15] in terms of distortions of the proton spectrum due to baryonic (e.g. Δ) and nuclear (e.g. ${}^5\text{Li}$) resonance decay.

Fig. 3 shows the extracted flow and temperature parameters as a function of bombarding energy for the most central collisions. Both parameters increase with energy. Also shown are the results of fits to energy spectra generated by a QMD model with momentum-dependent interactions [16] and with a BUU transport model that incorporates the emission of complex fragments up to mass $A = 3$ [17]. A geometric impact parameter distribution in the range $b = 0 - 3$ fm was used for the calculations. Uncertainties in the parameters for the model fits are of the same order as those for the data. As with the data, fits to the calculated spectra are significantly better with a finite flow parameter. Little dependence of the parameters on the equation of state is observed for either model.

It is interesting to evaluate the relative amount of kinetic energy tied up in radial flow [18,3]. If we estimate $E_{thermal} = 3T/2$ and $E_{flow} = (\gamma - 1)m$ then our results for central collisions indicate that about 45% of the kinetic energy goes into collective radial flow for deuterons (60% for α particles), with little dependence on bombarding energy. This is compatible with the FOPI results [3].

4. EXTRACTING CRITICAL EXPONENTS FROM THE DATA

The critical exponent analysis is applied to the data from Au+C collisions at 1.0A GeV. For each event, we determine the multiplicity of charged fragments, m , and the number of charged fragments, n_Z , of nuclear charge Z . We then construct the moments of order k of this distribution:

$$M_k(m) = \sum_Z Z^k n_Z(m). \quad (2)$$

Campi [5] was the first to suggest that the *methods* developed to study large percolation lattices may be relevant to the analysis of multifragmentation data. In percolation theory the moments of the cluster distribution contain the signals for critical behavior [8]. Quantities that display divergent behavior in macroscopic systems still show a peaking behavior in finite sized systems. In fact, it is well known in percolation theory how various quantities scale with system size [19]. In our analysis we have used the *methods* developed for determining percolation critical exponents to extract the critical exponents for nuclear matter from the moments of the fragment charge distributions.

We assume that m plays the same role as p in percolation [5]. We refer to the region in m below m_c , the critical multiplicity, as the ‘liquid’ phase and the region above m_c as the ‘gas’ phase. Following Stauffer [8], we omit the biggest cluster (fragment), denoted Z_{\max} , from the sum of Eq. 2 when we are on the liquid side of the phase transition. Physically, Z_{\max} corresponds to the bulk liquid in an infinite system. The critical exponents γ , β , and τ for large systems are given by

$$M_2 \sim |\epsilon|^{-\gamma}, \quad Z_{\max} \sim |\epsilon|^\beta, \quad \text{and} \quad n_Z \sim Z^{-\tau} \quad \text{for } m = m_c \quad (3)$$

where $\epsilon = m - m_c$ is the distance from the critical multiplicity.

Eqs. 3 can be applied to thermal systems as well as to percolation. In a thermal system, M_2 describes the isothermal compressibility which diverges at the critical point. In percolation it is the fluctuations of the mean cluster size. In an infinite system Z_{\max} is the order parameter of the transition. In a fluid system the order parameter is represented by the difference in density between the liquid and gas phases. This quantity is nonzero only below the critical temperature and vanishes at the critical point. Finally, τ determines the cluster distribution at the critical point. In small systems the singular nature of the equations is influenced by finite size effects.

The critical exponents are determined following the procedure developed in Ref. [20]. The first step is to use the second moment to determine γ . In percolation theory finite size effects can be offset by adjusting p_c from its infinite lattice value until one obtains power law behavior with the same value for γ in M_2 on both the ‘liquid’ ($p < p_c$) side of the transition and on the ‘gas’ side ($p > p_c$) (for bond breaking percolation). We have taken the same approach using multiplicity. We seek that value of m_c that gives the same value of γ for both the gas and liquid sides. The value of γ can depend on the region of ϵ used since finite-size distortions dominate as $\epsilon \rightarrow 0$, and signatures of critical behavior vanish for large ϵ , i.e., in the mean field regime.

The determination of the exponents was made by first selecting those values of m_c for which γ_{liquid} and γ_{gas} differed by no more than 10%. The distribution of m_c 's satisfying this matching criterion is peaked at 26. We have chosen $m_c = 26 \pm 1$ for our subsequent

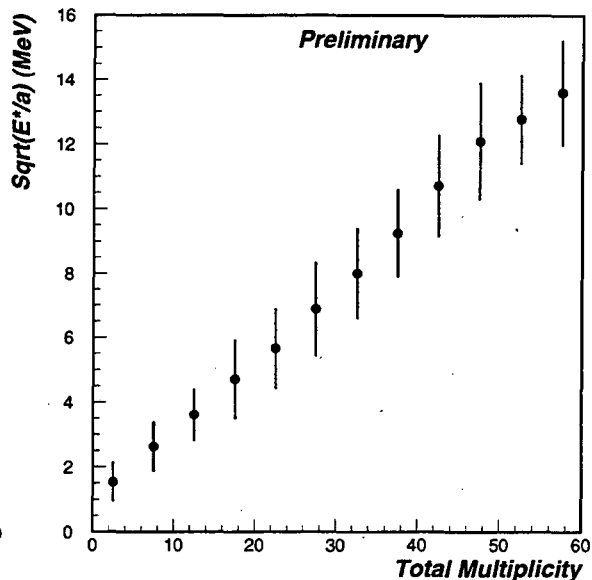
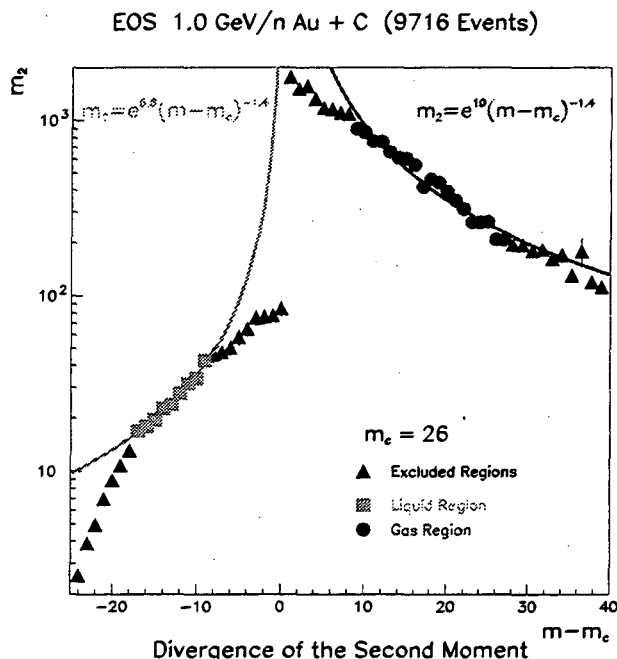


Figure 4. Example of the determination of the critical exponent γ for particular gas and liquid fitting regions. Figure 5. Model dependent temperature of the system as a function of multiplicity.

analysis. For each of these values of m_c we make many determinations of γ , β , and τ by varying the fitting region. Fig. 4 shows the second moment, M_2 , as a function of the distance from the critical multiplicity. The different points represent the Au+C data at 1.0A GeV. The triangles show the excluded areas (around the critical multiplicity and the mean field regions), the squares the liquid region, and the circles the gas region chosen. The solid curves represent the fits with Eq. 3 in the liquid and gas regions, respectively. The discontinuity at m_c is due to the fact that the largest fragment is omitted on the liquid side. The value of β was determined by fitting Eq. 3 to the liquid side. The exponent τ was determined from the slope of $\ln(M_3)$ vs $\ln(M_2)$ [5], where we have used only the gas branch of the plot. We also determined τ using Eq. 3 and obtained consistent results. The final values for the exponents are calculated by averaging all 370 trials made for the three choices of m_c . They are reported in Table 1. The errors listed there are a measure for the variation in those trials.

The values extracted by this procedure do not depend critically on our choice of a 10% slope matching criterion. Repeating our analysis requiring a more stringent 3% matching does not alter the values of the exponents.

The analysis so far assumes that all of the charges are associated with multifragmentation. However, protons are also emitted during the prompt stage of the reaction and can be evaporated from fragments. Protons from both of these sources should in principle be excluded from the multiplicity and moments. Using a method employed at lower energies [21], we have determined that there is a linear relation between the total observed multiplicity and that associated with the projectile fragment decay alone. Furthermore, the moments are dominated by large charges and removing protons has little effect on their

Table 1

Critical multiplicity and exponents for Au projectile fragmentation and other 3-dimensional systems.

Quantity	Experiment	Liquid-gas	Percolation	Liquid-gas mean field
m_c	26 ± 1			
γ	1.4 ± 0.1	1.23	1.8	1.0
β	0.29 ± 0.02	0.33	0.41	0.5
τ	2.14 ± 0.06	2.21	2.18	2.33

value. Thus the exponents are essentially unaffected by the inclusion of cascade protons.

For comparison with the data we have selected several 3-dimensional systems possessing a scalar order parameter, liquid-gas [22], percolation [8], and the mean field limit of the liquid-gas system. These values are also listed in Table 1. When comparing the experimental exponents with the others listed in the table, it is interesting to see that τ is close to 2.2 in all cases. The exponents extracted from the fragmentation data are close to those of the liquid-gas system and they differ from either the percolation or liquid-gas mean field results. For macroscopic systems, the critical exponents describe the power law behavior of thermodynamic quantities as the critical point is approached. We expect critical behavior to be effectively observable in finite size systems as long as the characteristic length and the number of degrees of freedom are sufficiently large.

Our analysis has been done under the assumption that the multiplicity plays the role of p in the percolation model. The relevant parameter for the liquid-gas system is the temperature T . Following a technique developed by Cussol and co-workers [21] we have tried to separate the sources and to perform a moving source fit (with the fragments measured in the TPC only for the time being). We have summed the kinetic and binding energies of all fragments, including neutrons. This yields an estimate of the excitation energy E^* for each event. Assuming a degenerate Fermi gas and a level density parameter $a = A/10$, temperature and excitation energy are related, $E^* = aT^2$. Fig. 5 shows that the temperature calculated this way depends linearly on the total multiplicity over a large range of multiplicities.

5. SUMMARY

Detailed measurement and analysis of fragment emission has led to new results in different areas. Large collective flow has been observed in several experiments. The EOS data show that the energy spectra of light particles emitted at midrapidity in Au+Au collisions can be well described in terms of a radially-expanding, thermal source with a common flow and a common temperature parameter for deuterons, tritons, ^3He , and α particles. Radial flow in central collisions increases as a function of bombarding energy. QMD and BUU model calculations reproduce the temperature and flow parameters satisfactorily. Very little dependence of the radial flow strength on the equation of state is seen in the models. Flow accounts for about 50% of the energy of light particles emitted at midrapidity from central collisions at all bombarding energies. A detailed investigation of the flow as a function of emission angle and impact parameter is under way [15].

We have analyzed the fragments emitted in Au+C reactions at 1.0A GeV with a tech-

nique borrowed from percolation theory. The influence of finite size effects has been taken into account by our procedure. We have been able to extract independently the values of three critical exponents from the data. These exponents are close to the values of the liquid-gas system. The analysis of systems of different size is in progress to further characterize this phenomenon.

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of Nuclear Physics of the U.S. Department of Energy under Contracts DE-AC03-76SF00098, DE-FG02-89ER40531, DE-FG02-88ER40408, DE-FG02-88ER40412, DE-FG05-88ER40437, and by the National Science Foundation under Grant PHY-9123301.

REFERENCES

1. J. Aichelin, Phys. Rep. 202, 233 (1991); H. Stöcker and W. Greiner, Phys. Rep. 137, 277 (1986); H.H. Gutbrod, A.M. Poskanzer and H.G. Ritter, Rep. Prog. Phys. 52, 1267 (1989).
2. K.G.R. Doss et al., Phys. Rev. Lett. 59, 2720 (1987).
3. S.C. Jeong et al., Phys. Rev. Lett. 72, 3468 (1994).
4. J.E. Finn et al., Phys. Rev. Lett. 49, 1321 (1982); R.W. Minich et al., Phys. Lett. B 118, 458 (1982).
5. X. Campi, J. Phys. A19, L917 (1986); X. Campi, Phys. Lett. B 208, 351 (1988).
6. W. Bauer, Phys. Rev. C 38, 1297 (1988).
7. P. Kreuzt et al., Nucl. Phys. A556, 672 (1993).
8. D. Stauffer and A. Aharony, Introduction to Percolation Theory, second edition (Taylor and Francis, London 1992).
9. W.C. Hsi et al., preprint MSUCL-930 (1994); W.G. Lynch et al., these proceedings.
10. G. Rai et al., IEEE Trans. Nucl. Sci. 37, 56 (1990).
11. W. Christie et al., Nucl. Instr. Meth. A255, 46 (1987).
12. S. Albergo et al., Nucl. Instr. Meth. A311, 280 (1992).
13. P.J. Siemens and J.O. Rasmussen, Phys. Rev. Lett. 42, 880 (1979).
14. K.G.R. Doss et al., Phys. Rev. Lett. 57, 302 (1986).
15. M.A. Lisa et al., preprint LBL-35504 (1994).
16. G. Peilert et al., Phys. Rev. C 39, 1402 (1989).
17. P. Danielewicz and Q. Pan, Phys. Rev. C 46, 2002 (1992).
18. W. Bauer et al., Phys. Rev. C 47, R1838 (1993).
19. D. Stauffer, Phys. Rep. 54, 1 (1979).
20. J.B. Elliott et al., Phys. Rev. C 49, 3185 (1994).
21. D. Cussol et al., Nucl. Phys. A561, 298 (1993).
22. H. E. Stanley, Introduction to Phase Transitions and Critical Phenomena (Oxford University Press, 1971).

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720