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What lies beyond the Mean-field ?

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With Large Counter Arrays

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MASTER

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This talk will address statistical theories that attempt to understand the physics of heavy-ion collisions at excitation energies near 15 MeV per nucleon. Before I begin, I would like to comment on the title in Fig. 1. The original title was, " What Lies Between the Mean Field and the Lorentz Desert ? " . Now the question that is being posed has changed, and at the bottom of the figure one of the answers is, " the Lorentz Desert " . Unfortunately, I will not have sufficient time to discuss this issue. This has to do with the question of measuring the equation of state at high density. G.E. Brown has argued, that in relativistic heavy ion collisions, we are not viewing nuclear matter at high densities because of particular Lorentz transformation properties of meson exchange forces[1]. Hence the original title. I refer you to the discussion in Ref. 1.

Thermal models, of the type I shall be discussing, have become predominant at energies more than an order of magnitude higher than those here[2], and you shall endeavor to contrast them with the complex dynamical models based on mean fields with two-body collision terms[3] that we heard about yesterday from Das Gupta. These have been most successful in understanding the phenomena of fusion and deep inelastic scattering at lower energies. In this talk I want to discuss the question of the nuclear liquid-gas phase transition[4], and how it might influence heavy ion collisions in this energy domain. It is fairly well established that continuous nuclear matter undergoes such a transition in this energy range[5], however its realization in violent heavy ion collisions is presently controversial and must be further studied experimentally.

A menu of the talk is given in Fig. 2. We shall begin by examining very simple spallation[6] and percolation[7] models which yield inclusive mass spectra, and note that a kind of *ergodic* [8] process is taking place which I would like to state as follows: *All models will eventually correctly predict the behavior of an average particle in an average event.* I shall then discuss two complex statistical models[9,10] which try to deal with the phase

transition, including the fragmentation of real nuclei and with interactions between the outgoing fragments. There are two principal assumptions that need to be tested in these calculations, 1) the existence of an intermediate state, independent of entrance channel effects, from which the disassembly proceeds, and 2) the role of the entropy in the expansion and disassembly phase. Thirdly, I will briefly discuss Hanbury-Brown Twiss correlations from two points of view, as a diagnostic of the gas phase[11], and then also a possible way to extract the temperature[12]. We have already discussed the equation of state at high densities, and I refer those interested to Ref. 1.

Let us first consider spallation as shown in Fig. 3. These have been discussed at length by Hüfner[6], where he notes this approach is more that 20 years old. Spallation is generally assumed to be a peripheral process, and thus tells us very little about the nucleus-nucleus dynamics. As a two step process which we might think of as a cascade-evaporation mechanism: 1) the nuclei are excited to an energy E^*, and the energy loss cross section, $d\sigma/dE^*$, is obtained, and 2) for a given amount of excitation energy, ε, the fragment mass is changed by one unit. In Ref. 6, ε is an adjustable parameter, and the energy loss cross section is computed using Glauber theory. The mass spectra have the power law behavior as shown in Fig. 4. It is interesting to note that, with the simple two-step process, the integrated cross section has the general form,

$$\mathrm{Ln}(\sigma) \approx -\tau \ln(A) + (c)\frac{A}{A_T} .$$

Unfortunately, as we shall see, other models can exhibit a similar type of behavior.

Percolation calculations have been carried out by several authors[7,11] and the lattice model of Mosel as described in the Fig. 5 is particularly novel. In this model nucleons in a nucleus are assumed to occupy sites on a regular cubic lattice. The links between the sites supposedly account for the binding of the nucleons. In the cubic lattice. most nucleons are linked to six nearest neighbors. A random number generator is used to break the bonds,

and the location of where the bonds are broken is random. Distributions of lattices having the same amount of damage are assumed to be equally probable. In this treatment, certain connected patterns are identified as nuclear fragments, and one observes a type of behavior which is similar to a phase transition as shown in Fig. 6. Here we have the probability of percolation, the mean multiplicity, the fluctuation in the multiplicity and the exponent in the inclusive cross section as a function of the damage concentration. When the damage concentration becomes sufficiently large, the system undergoes a type of collapse, or disassembly, note that the exponent goes through a minimum at the critical concentration. In a continuous system, the yield of fragments obeys a power law relation in which the critical temperature is related to the exponent[5]. The results from the lattice model are suggestive of a similar type phenomena. In Fig. 7 the results of a percolation calculation are compared to high-energy, proton-induced inclusive data. These data span an energy range between 80 and 350 GeV, and as we might have expected, the calculation can be made to fit the data extremely well.

The above models, although statistical in their foundations, are probably too simple to fully explain multifragmentation data. Recalling the ergodic hypothesis, stated again in Fig. 8, the success of a variety of models of this type suggest that more complex measurements are needed to understand these reactions, and that also necessitates a more systematic theoretical approach.

Bondorf and co-workers[9] have built on the participant-spectator model to formulate a more complete theory of multifragmentation. There are several questions, shown in Fig. 9, that we should keep in mind as we proceed with the discussion. These are as follows: 1) how do we go from a mean-field with 2-body collision terms to a hot, compressed state of matter, 2) what about equilibrium, and the role of entropy, 3) does the liquid-gas phase transition play a role? On a more practical level, we shall need to deal with phenomena displaying a large multiplicity of highly excited fragments. In Fig. 10 the various stages in their model are depicted. The most important is the identification of an intermediate or

transition state. This state is near thermodynamic equilibrium and is supposedly formed by dynamical processes which compress and heat the nuclei . It is also assumed that all of this matter, having mass A and total charge Z, is confined within a volume V, and has a total energy E. On a short time scale, the system *cracks* accompanied by expansion and subsequent decay and evaporation . The probability of obtaining different final states is determined from the statistical weights for particular fragment configurations. It is highly unlikely that all of these dynamical processes occur at the same time as indicated here. However, it is more to the point to ask whether it is possible to measure properties of the transition state.

Their approach, as summarized in Fig. 11, closely parallels that of a microcanonical ensemble. The partition n(a,z) is defined so as to count different fragment arrangements, and determine the mass, charge, and multiplicity of fragments,

$$\sum_{a,z} n(a,z)\, a = A \qquad \text{mass}$$

$$\sum_{a,z} n(a,z)\, z = Z \qquad \text{charge}$$

$$\sum_{a,z} n(a,z) = m \qquad \text{multiplicity}$$

Since this formalism possesses neither a canonical or microcanonical ensemble, a partition function is constructed by counting arguments, and then the free energy, entropy and statistical weights are calculated. Note that fragments are constrained to have a mean energy, and that fluctuations in the fragment energy are not included in this treatment. From the statistical weights, all the observables of the system can be determined. In Fig. 12 the

total energy is given as the sum of all of the fragment energies and a global Coulomb energy,

$$E_{tot} = \frac{3}{5}\frac{Z^2e^2}{R} + \sum_{a,z} n(a,z)\ E(a,z)$$

Also, they assume that after the breakup that fragments cease to interact, and move freely throughout the volume V. This limitation is fairly severe and probably affects the final temperatures and spectral distributions by as much as 50 per cent[13]. In particular, it suppresses the Coulomb interaction between the fragments as during the expansion. We shall return to this point later. The fragment energy is composed of several parts. Let us look at liquid drop bulk and surface terms which contribute to the internal energy of a fragment. The bulk energy is given as,

$$\text{Bulk energy} = \left[W_0 + \frac{T^2}{\varepsilon_0} \right]$$

The first term in the above equation is the bulk energy of nuclear matter, and the second term is the low temperature expansion of a fermi gas. However, the level density parameter, ε_0 is adjusted to fix the mean excitation energy of a fragment. This relation ignores any change in the energy due to compression of matter in the bulk and is probably not correct for small fragments and at low excitation energy. Note that fragments with mass less than four are assumed to comprise the gas phase. The surface energy term is ,

$$\text{Surface energy} = \left[\beta - T\frac{d\beta}{dT} \right] A^{2/3}$$

where the surface free energy is given by,

$$\beta A^{2/3} = \beta_0 A^{2/3} \begin{cases} \left[\dfrac{T_c^2 - T^2}{T_c^2 + T^2} \right]^{5/4} & T \leq T_c \\ 0 & T > T_c \end{cases}$$

This is an important term in that the exponent, the critical temperature, and the parameter β_0 are intimately connected to the phase transition in the infinite medium. The surface energy plays a key role in determining the fragment size during the expansion phase, and is strongly dependent on the liquid-gas phase parameters. In a finite system undergoing such a transition the surface tension is proportional to the Gibb's free energy times the correlation length associated with the fluctuations at the critical temperature. At this point contributions to the energy from shell effects, deformations and pairing are neglected. In this model the contribution to the total energy from the kinetic energy of the fragments is included by introducing a new parameter χ, so that the effective volume is $V_{eff} = \chi V$. Let us review some of the assumptions: 1) the transition temperature T is a constraint on the system which is fixed by overall energy conservation, 2) the fragment multiplicities are constrained by overall charge and mass conservation, 3) assume the system is held in thermal equilibrium with an external heat bath.

Results of calculations with this model are shown in the Figs. 13,14,15 for a transition state having 100 particles. The onset of fragmentation begins at an excitation energy of 3.5 MeV per nucleon. Note, there is a corresponding sharp increase in the mean multiplicity and also a lowering of the temperature as the system expands. The dashed curve depicts the temperature dependence of a free N-N gas. The cooling occurs because, as fragments form, there is an increase in the available volume in which they move. At an

excitation energy near 16 MeV there is a rapid rise in the multiplicity of emitted fragments which occurs as the liquid gas phase transition breaks up the fragment's surface. Here the temperature of the the system again decreases and eventually increases again. In Fig. 14 we see that the breakup density has large fluctuations at the onset of fragmentation and reaches an approximately constant value at about a third of the nuclear matter value. Mass spectra for this case are shown in Fig. 15. At low excitation energy the mass distribution is sharply peaked at a small value of the mass; however, at higher excitation energies this behavior changes dramatically.

I would like to note the following two points. The fragment mass distribution is sensitive to the Coulomb interaction between the fragments. It stabilizes the production of heavy fragments and yields a much lower temperature. The spectra are changed by the interaction between fragments; they are shifted to higher energies with much larger widths.

A similar approach has recently been developed by Koonin and Randrup[10], as noted in Figs. 16,17. However, they employ a full microcanonical ensemble which automatically incorporates interfragment forces. Except for these details, they employ the same general assumption of a transition state from which they calculate the disassembly. In their studies they note an important behavior of the fragment level densities. The number of excited states of the fragments that are included in the ensemble are important in determining the final mass spectra. Thus they include in their description of the fragment density of states a parameter that tries to account for the finite lifetime of these highly excited states. Recall, in the Bondorf work, that the intrinsic density of states is approximated to be the same as that of a zero temperature fermi gas. The treatment here assumes that the fermi gas density of states is modified at high excitation energy by ,

$$\rho(\varepsilon) \quad = \quad \rho_{fg}(\varepsilon) \quad \exp[-\varepsilon/\tau_0]$$

and yields an effective temperature,

$$\tau_{eff}^{-1} = \tau^{-1} + \tau_0^{-1}$$

In this way the parameter τ_0 can be interpreted as the maximum temperature attainable by the nuclear fragments.

Results of these calculations are shown in Fig. 18. Here we see the mean fragment mass is not sensitive to the choice of a limiting temperature. All of the other observables, the mean excitation energy, the specific heat, and the entropy show a sensitivity to this parameter, and hence to the level density of the fragments. These are calculations with a grand canonical ensemble, the results with the canonical ensemble are given by the blue circles, and those for a microcanonical ensemble are the red circles. Figure 19 shows the effects on the density and the importance of the interaction between the outgoing fragments. On the left-hand side of the figure, the effects of turning off the semi-empirical Coulomb energy; again, the blue circles indicate the results for the microcanonical ensemble. On the right-hand side of the figure the results for three combinations of the interfragment interaction are compared. As stated in Fig. 20, it is important to also keep in mind that these calculations are simple simulations which do not include the vapor phase. However, it has been incorporated in the compression expansion studies in Fig. 21. Even though, there is no direct parameterization of the phase transition, some of the features of the liquid-gas transition are apparent. The possible influence of the phase transition on the mean mass and the mean excitation energy of the fragments are shown for the expansion-compression cycle.

These models involve two important ideas, (see Fig. 22), which should be further explored. The first is the question of the transition state. We believe that heavy-ion reactions at these energies support a large number of separate processes and that is, in part, why statistical approaches seem sensible. It is assumed that some of these processes go into the formation of a transition state. Which processes comprise this state, and what is their space-time structure are questions which might be answerable by further experiment.

The second point at issue is the temperature of the final fragments. We have observed that details of the spectra and the temperature depend sensitively on mutual interactions between the fragments and their excitation spectra. Thus, measurements of the excitation spectra of the final fragments can yield information on the final temperatures. Both of these questions have recently been considered employing measurements of two-particle correlation functions.

It was pointed out nearly 10 years ago, for heavy-ion reactions, that inclusive two-proton cross sections carry information on the space-time structure of the emitting source[14]. From the two-particle cross section, and the inclusive singles cross sections, the correlation function, R(q), is defined by,

$$\frac{d^6\sigma}{d^3p_1 d^3p_2} = \sigma_0^{-1} \left[\frac{d^3\sigma}{d^3p_1} \right] \left[\frac{d^3\sigma}{d^3p_2} \right] [R(p_1,p_2) + 1]$$

The notation here is that of Ref. 14, σ_0 is a normalization constant. This function has been discussed by many authors and typical measurements are shown in Fig. 23. These are measurements of the proton-proton correlations in the reaction $^{16}O + ^{197}Au$ at an energy of 25 MeV per nucleon[15]. Gaussian source radii are also indicated in the figure. In a recent preprint[16], Pratt and Tsang have shown that this correlation function can be determined from the phase space distribution function F(p,r) . They note that the emission from a long lived source will *stretch* this function along the direction of p, whereas the emission from an expanding source would not have this characteristic. In their treatment, Pratt and Tsang obtain a correlation function which differs from that of Ref. 14 in that they integrate out the time dependence of the source, and obtain a function C(K,q) which is expressed as a function of the c.m. and relative momenta of the pair, respectively K and q. Information as to the lifetime and collective motion of the source is determined by measuring the total and relative momenta of the pair. A typical correlation function deduced from a prolate

Gaussian source is shown in Fig. 24 the longitudinal and transverse source sizes are respectively 12 fm and 3 fm. This illustrates the type of resolution needed to differentiate between the transverse and longitudinal directions. Figure 25 shows the longitudinal and transverse spread in F(p,r) for protons emitted from an evaporative source with an initial temperature of 10 MeV. The sizes are plotted as a function of the total energy of the emitted protons. The key signal for evaporative cooling is the strong elongation that rapidly diminishes with increasing particle energy. These results should be contrasted with the spread in the phase space distribution function from a hot exploding spherical distribution whose velocities increase linearly from the center of the coordinate system. . The drop in source size with increasing particle energy depends on the ratio of collective (flow) energy to thermal energy. The source in this figure corresponds to a velocity, $\beta = 0.3$ and a temperature of 10 MeV. The difference between this picture and the evaporation picture is in the degree of elongation.

Hanbury -Brown Twiss correlation measurements[17] between a variety of light particles in the reaction ^{32}S + Ag at an energy of 22.3 MeV per nucleon are shown in Figs. 26,27,28 . These are data taken at HHIRF by Awes, Obenshain, Plasil, Ferguson and Young all from Oak Ridge, in collaboration with Chen, Pochodzalla, Gelbke, Xu, and Lynch all from MSU. Here various light particles in coincidence with alpha particles are shown and exhibit several resonant-like structures in the correlation functions. These structures probably represent resonances from alpha decays of light nuclei, and if this is the case, will enable us to obtain fairly accurately the excitation energy of the emitting source. In Fig. 28, p-p correlation measurements from the ORNL-MSU group, are compared to different theoretical source calculations. I would like to note the structure in the data at large q for the Al and Ag targets. The correlation function, as it is defined here,

must eventually become one at sufficiently large q. Here we may be seeing evidence that there is a gas phase in these reactions.

My conclusion that I would like to leave you with is as follows. There is only one fundamentally new feature in this energy range, and that is the liquid-gas phase transition. It would be disappointing if we could come to terms with all of this heavy ion data solely as the dynamics of a mean field with collisions and learn nothing about this transition.

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What Lies Beyond the Mean-Field ?

* Heavy ion Collisions at $10 - 10^2$ MeV per nucleon

* Liquid Gas phase transition

* Lorentz desert

Fig 1

Statistical Models of fragmentatio
try and extract the underlaying "Collecti
nucleus - nucleus dynamics"

* Spallation Percolation

Ergodic Hypothesis

* Ensembles - Canonical, Micro canonic

transition State

Entropy

* h-BT Correlations

EoS at high density

Fig 2

Spallation

J. Hüfner et. al. Phys. Lett '86

$$A_p + A_T \xrightarrow[A^*]{} A + X$$

two-Step process (1968)

1) the projectile "looses" energy to the target forming a "prefragment" (intranuclear Cascade)

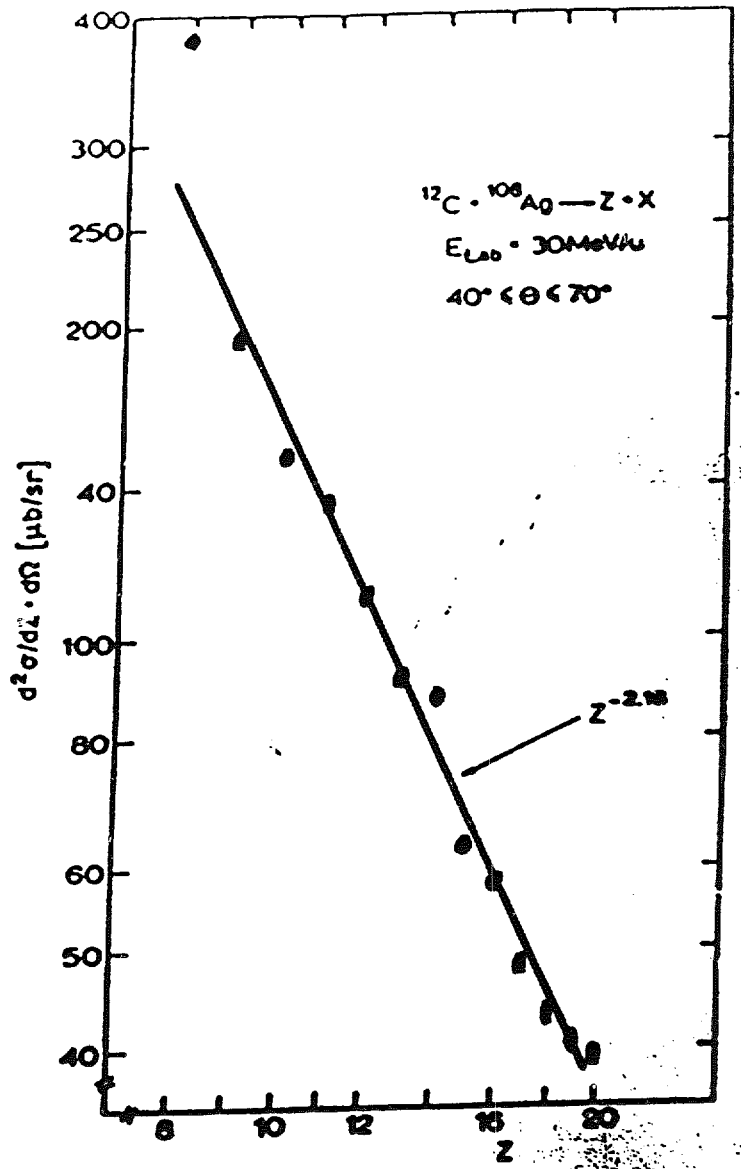
$\longrightarrow$ $d\sigma / dE^*$

2) For an amount of excitation "ϵ" one unit of mass is emitted

$$\frac{d\sigma}{dA} = \left[\frac{E^*}{A_T - A} \right] \frac{d\sigma}{dE^*}$$

(evaporation)

J. Hüfner J. de Physique C4 3 (1986)



$$\ln(\sigma) \sim -\tau \ln(A/A_T) + (\alpha)$$

A/A_T

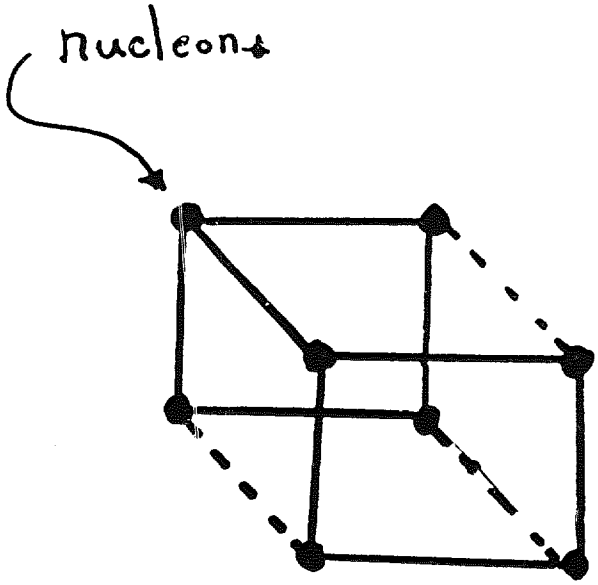
constante

Fig 4

percolation

Bauer Mosel Post

Nucl. Phys. A442 '86



"Each nucleon is linked to 6 nearest neighbors"

* Links are broken using a random number Generator
* Classes of events having a particular concentration of damage are organized into partitions
* different partitions having the same damage are equally probable

Fig 5

Bauer Mosel & Post

phase - transition

Prob.

multiplicity

Varience

$\sigma^2 = \langle m^2 \rangle - \langle m \rangle^2$

Exponent

$\sigma \sim A^{-\lambda}$

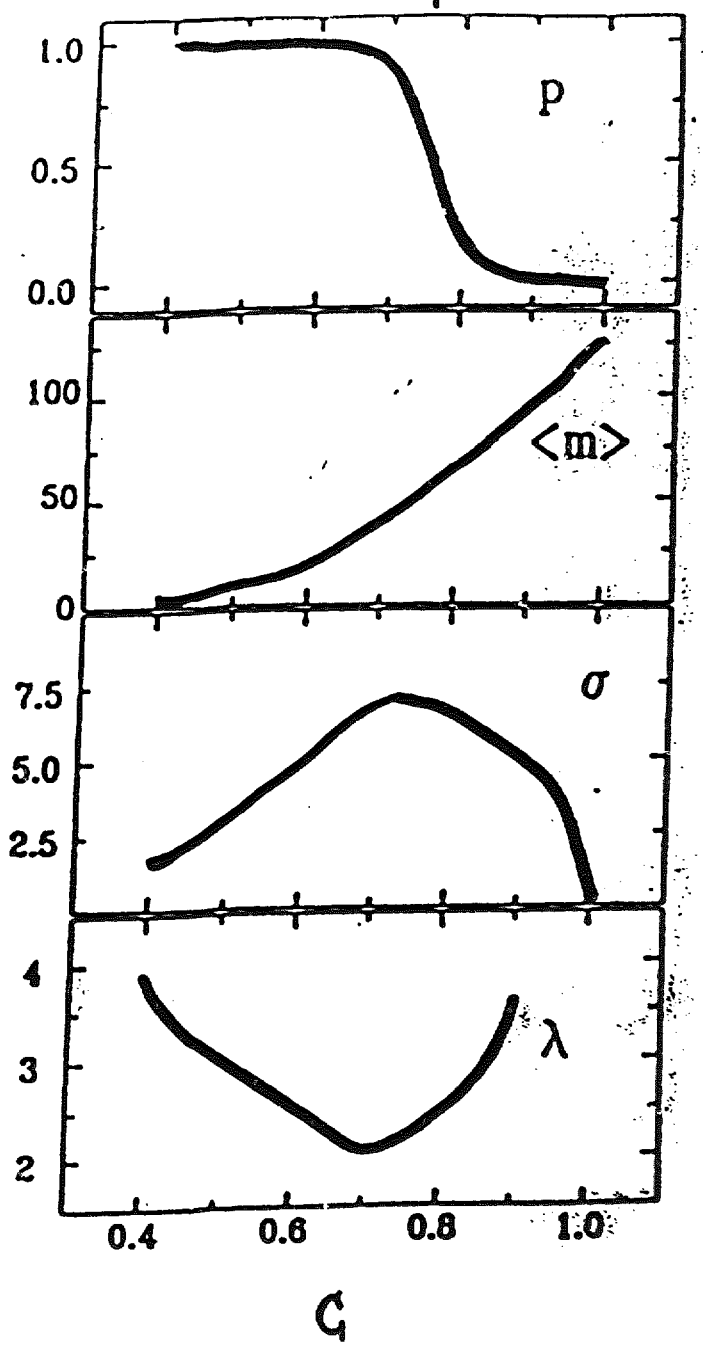
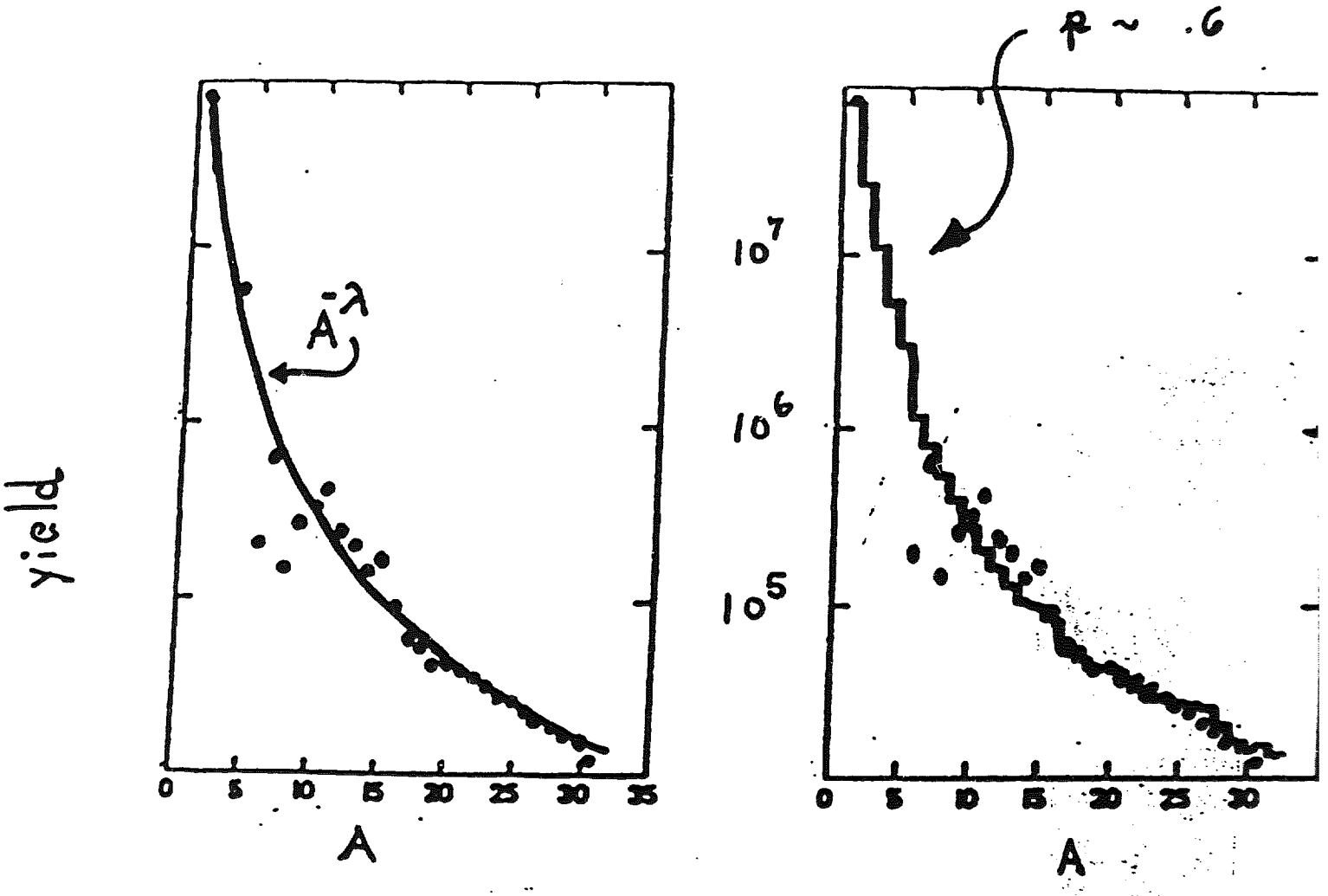


Fig 6

Mosel et. al.

$$p + Xe \longrightarrow A + X$$



data : "perdue" Phys Rev **C29** (1984)

$\lambda = 2.64$

Fig 7

"Ergotic Hypothesis"

"All models will eventually correctly predict the behavior of an average particle in an average event."

Fig 8

"More detailed Statistical Picture"

Questions

How do we go from a mean field with 2-body collision terms to hot compressed nuclear matter?

What about equilibrium, and what role does entropy have? time scales for the reaction?

What about the Liquid-Gas phase transition?

Need to deal with a Large multiplicity of fragments, possibly highly excited.

Fig 9

Bondorf et. al. Nucl. Phys. A443 '85
" " A444 '85

Volume V

A, Z

energy density E/V

Near thermodynamic equilibrium →

Assume an intermediate or transition state, that is prepared by a series of dynamical processes (Compression & heating)

Fig 10

Bondorf et. al.

partitions in a, z

$$\sum_{a,z} n(a,z) = m \qquad \text{multiplicity}$$

$$\sum_{a,z} n(a,z) = A \qquad \text{Mass}$$

$$\sum_{a,z} n(a,z) = Z \qquad \text{Charge}$$

"Partition"

$\{n(a,z)\}$ → $F(\{n(a,z)\}, T)$ ← free Energy

$$S = -\frac{\partial F}{\partial T}$$

entropy

$$W_f = \mathrm{Exp}\left[S_f(\{n\}, E) \right]$$

"Statistical Weights"

Total Energy $\longrightarrow$ temperature

$$E_{tot} = \frac{3}{5}\frac{Z^2 e^2}{R} + \sum_{a,z} n(a,z)\, E(a,z)$$

global Coulomb energy

Fragment Energy

bulk energy $\left[W_0 + \frac{T^2}{\varepsilon_0} \right] A$

Fermi Gas

"ε_0 – determines mean excitation in fragments"

Surface Energy $\left[\rho - T\frac{d\rho}{dT} \right] A^{2/3}$

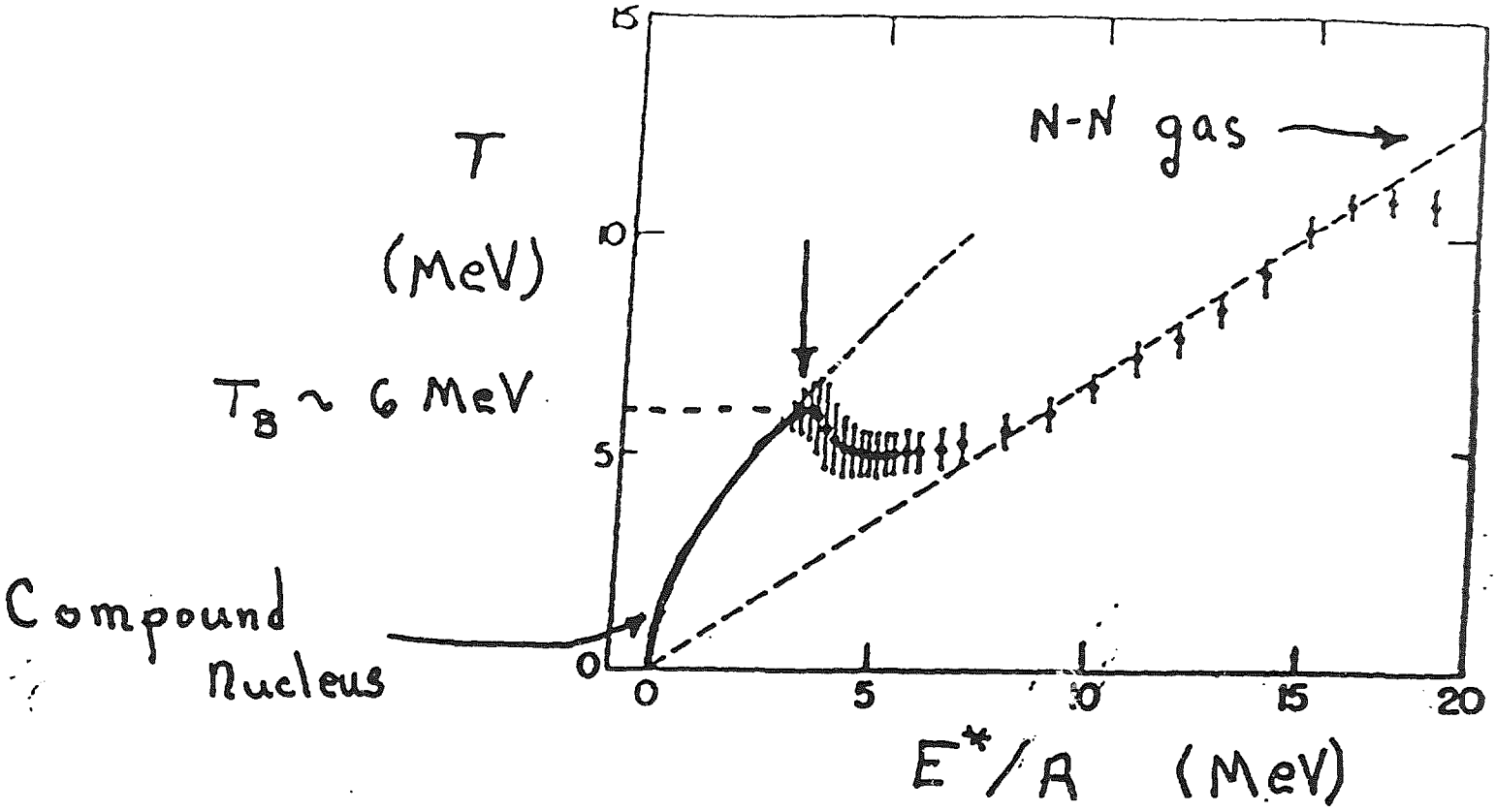
$$\rho/\rho_0 A^{2/3} = \left[\frac{T_c^2 - T^2}{T_c^2 + T^2} \right]^{5/4} \qquad T < T_c$$

Free Enegy

phase transition

Fig. 12

Bondorf et. al.



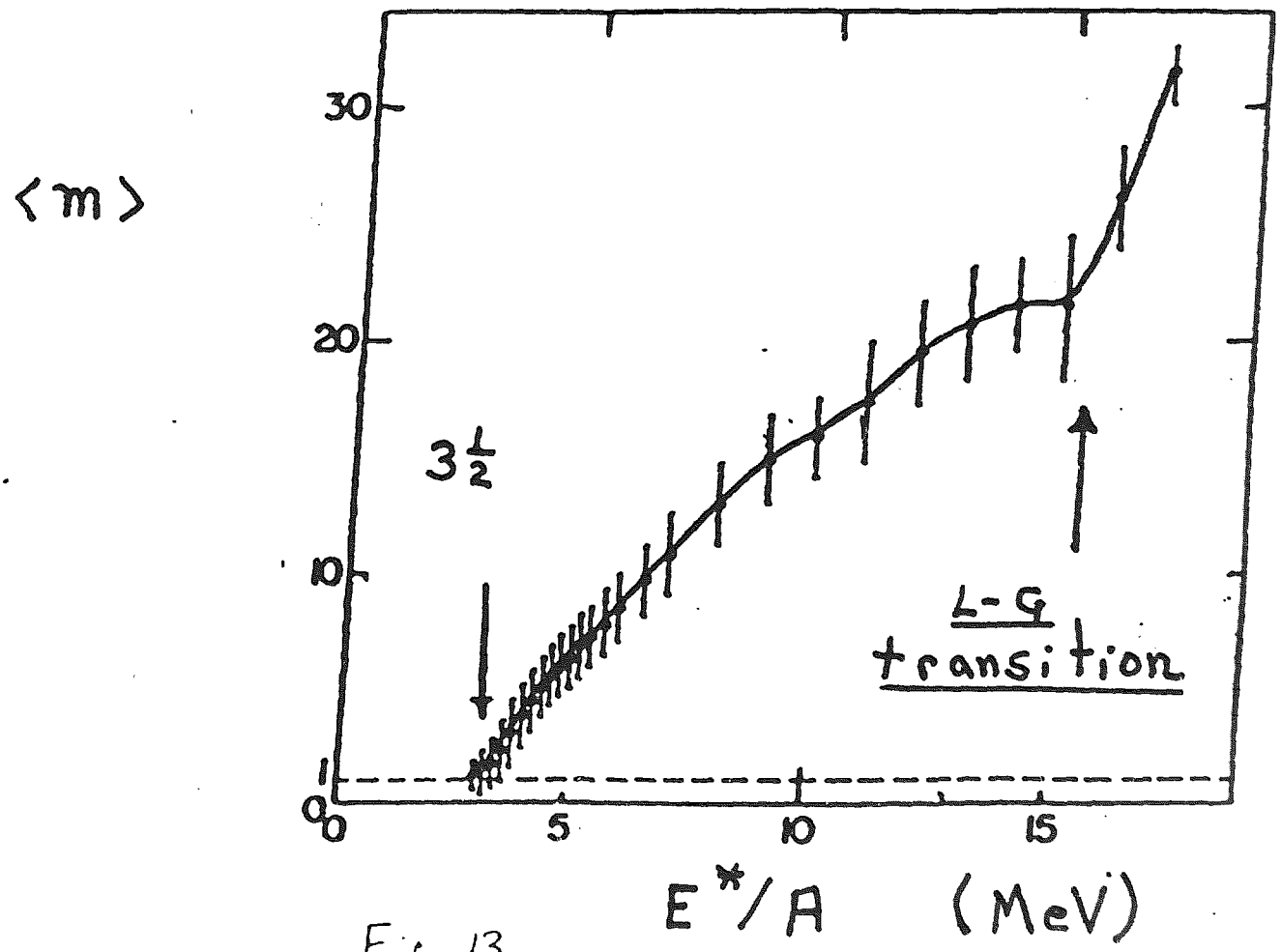
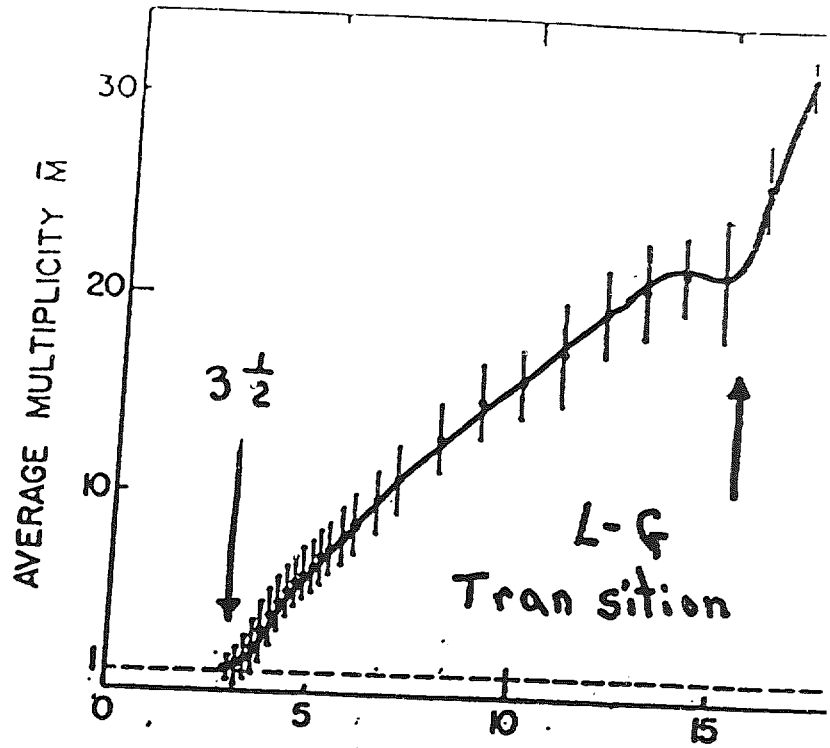


Fig 13

Bondorf et.al.

A = 100



"Large Fluxuations"

$\rho_0 / 3$

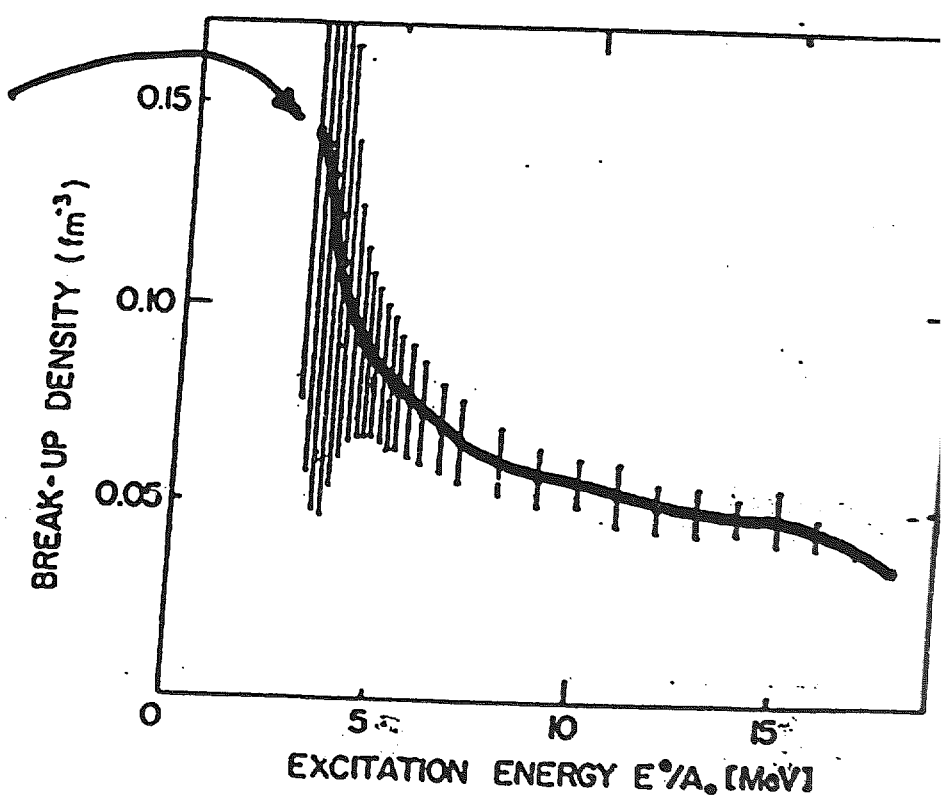


Fig 14

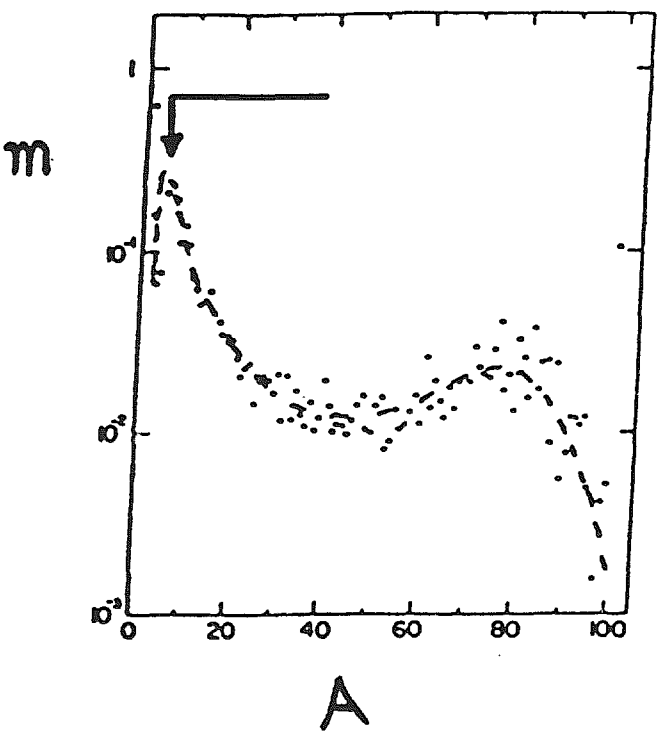
Bondorf et. al.

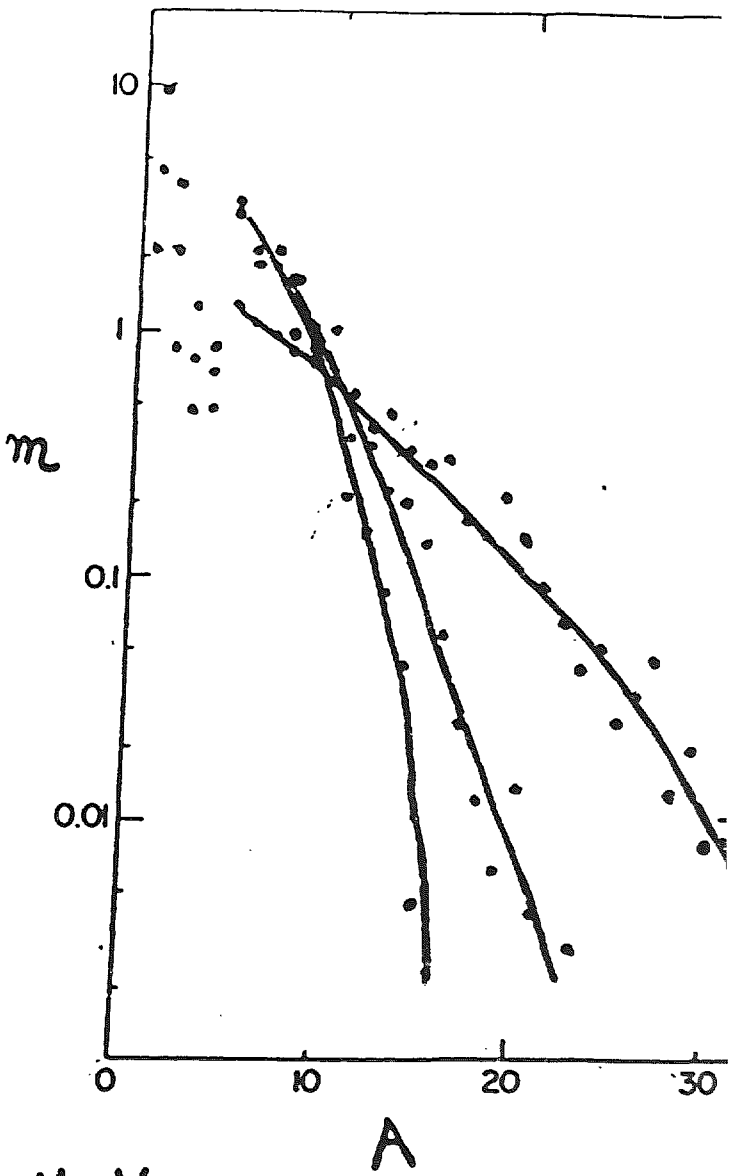
10^4 Monte Carlo runs

A = 100

E^*/A = 4 MeV

$\langle m \rangle \sim 3.7$





E^*/A = 12 MeV

E^*/A = 8 MeV

E^*/A = 16 MeV

Fig 15

"Macrocanonical Simulation of the disassembly"

Koonin & Randrup

M.a.p. Dec '86

Pgm available upon request

Koonin @ CALTECH.BITNET

Fig 16

Microcanonical density of States

$$\rho(V, A, E)$$

Fragentation Specified as:

$$F\{A_f, \vec{r}_f, \vec{P}_f, \mathcal{E}_f;\ f = 1, \ldots N_F\}$$

Energy Given by

inter-fragment 2-body pot.

$$E_F = \sum_f \left[\frac{P_f^2}{2mA_f} - B_f + \frac{1}{2} V_{ff'} \right]$$

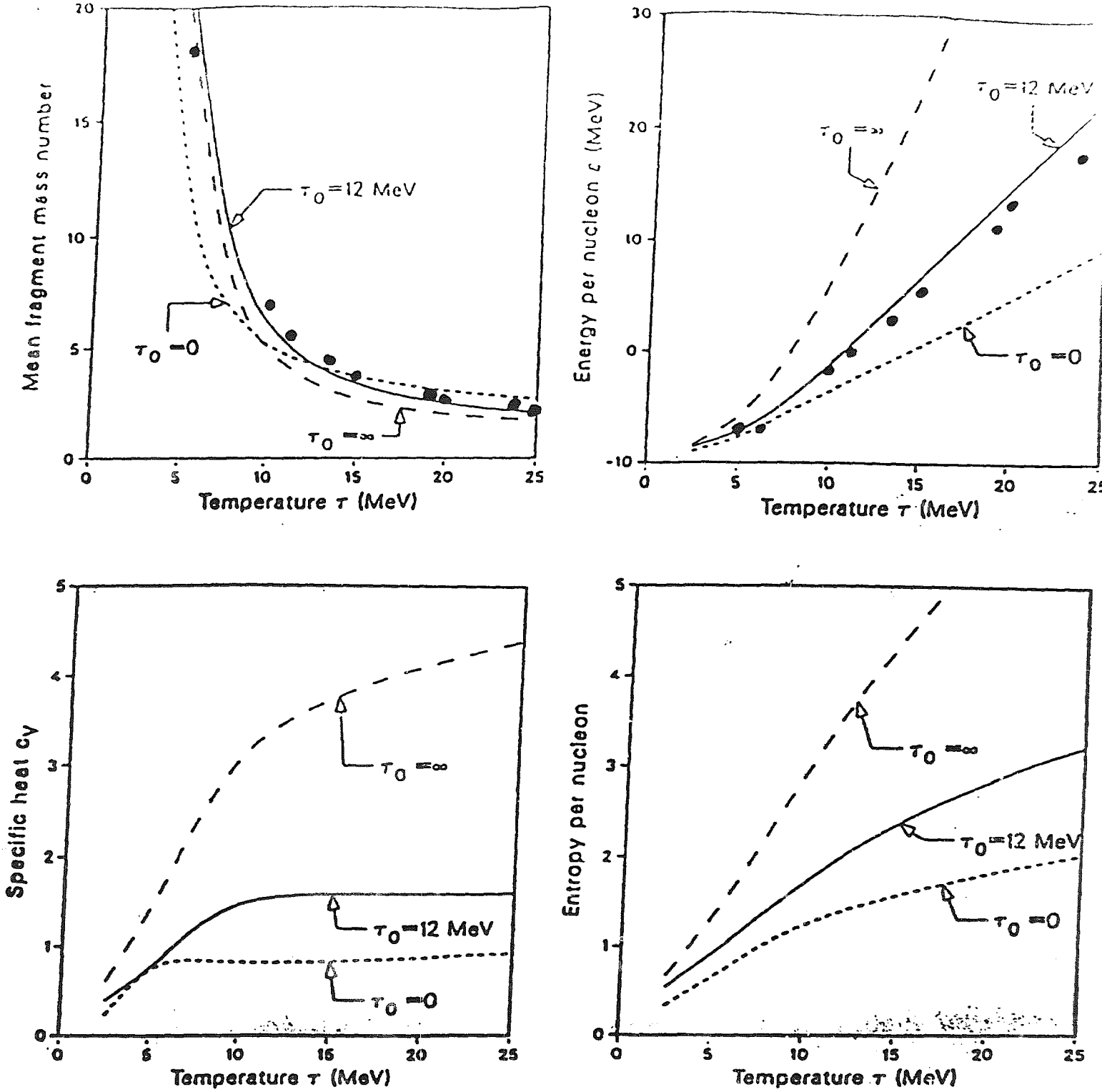
S.E. mass formula

fragment Level density

$$\rho(\varepsilon) = \rho_{fg}(\varepsilon)\, e^{-\varepsilon/\tau_0}$$

Limiting temperature

Fig 17



$A = 40, \rho = \frac{1}{2}\rho_0$

$\tau_0 = 12$ MeV

- Canonical
- Micro-canonical

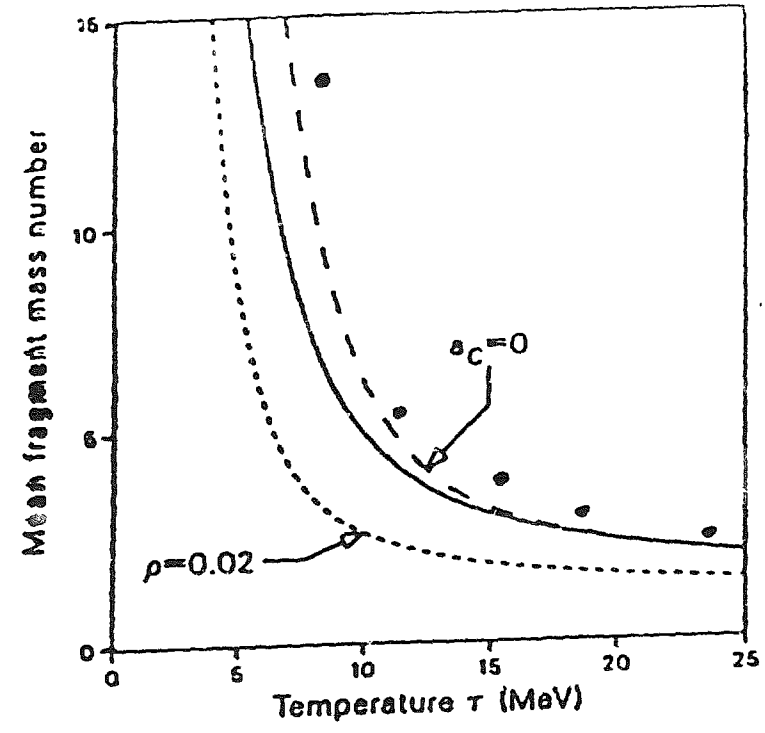
Fig 18

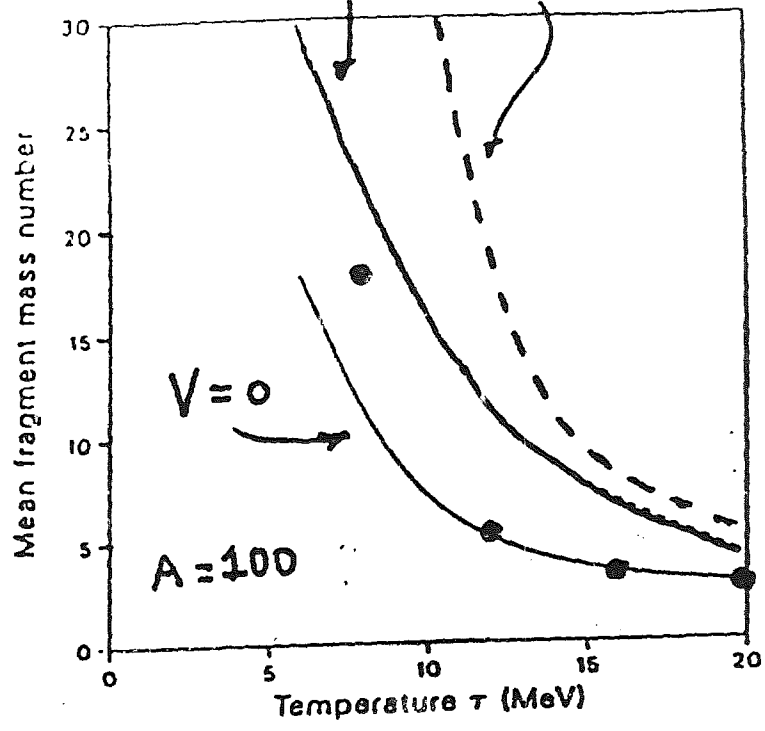
Koonin & Randrup

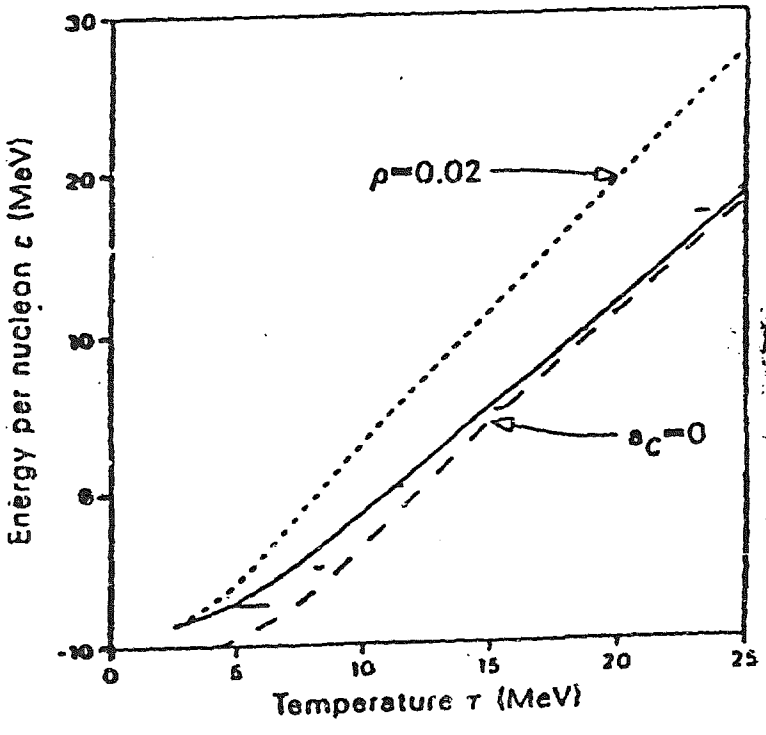
$A = 40 \quad \rho = \frac{1}{2}\rho_0 \quad \tau_0 = 12$ MeV

hard Sphere

+ Coul







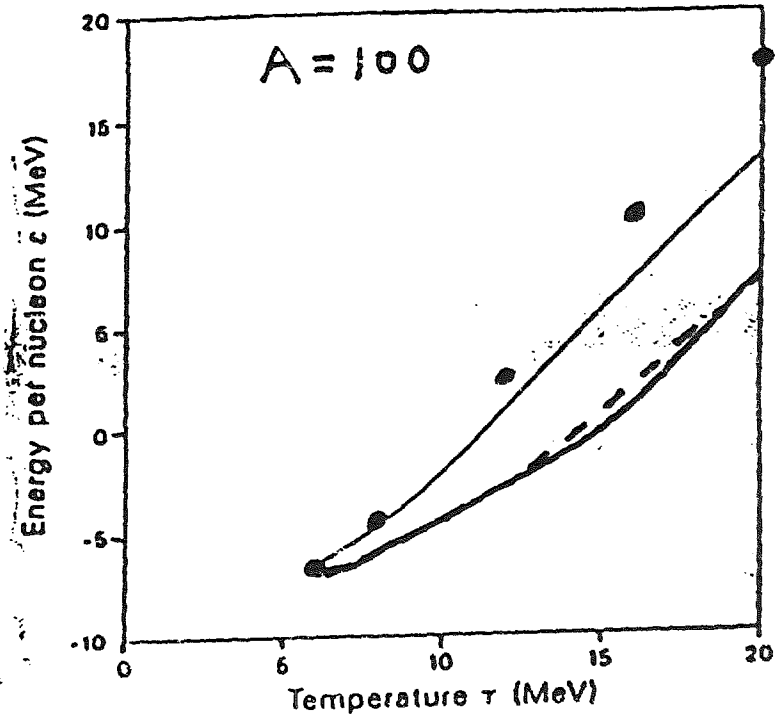


Fig 19

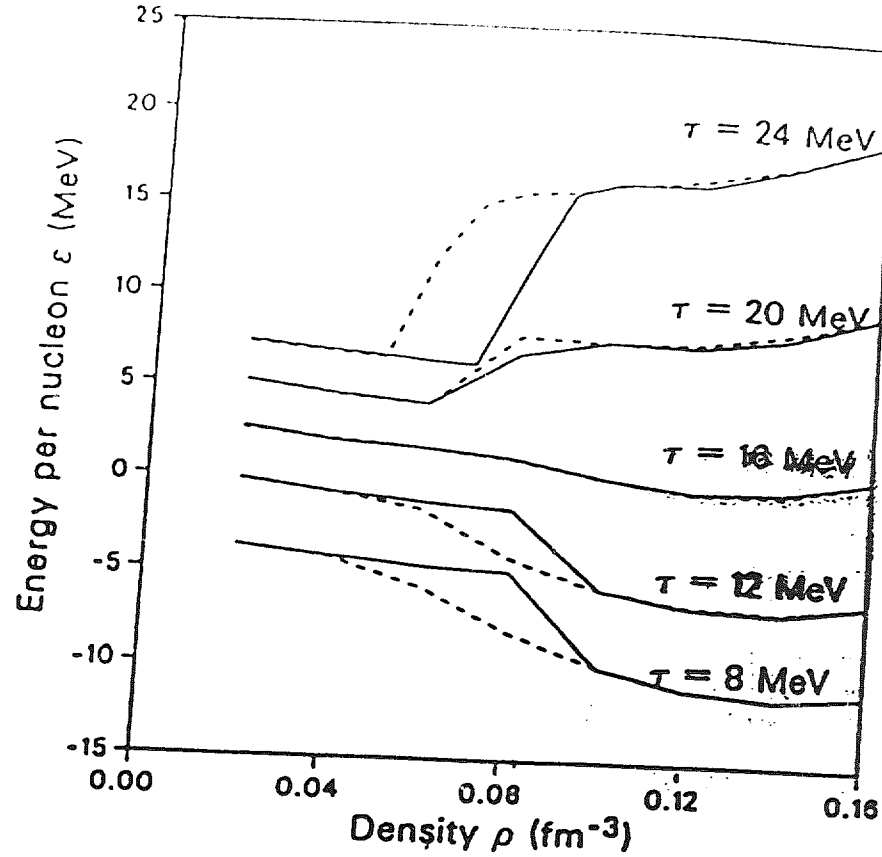
* Sensitive to the details of the inter-fragment pot.

* Level density of the fragments

No Gas!

Fig 20

A = 100



Compression - Expansion Cycle

Phase transition ?

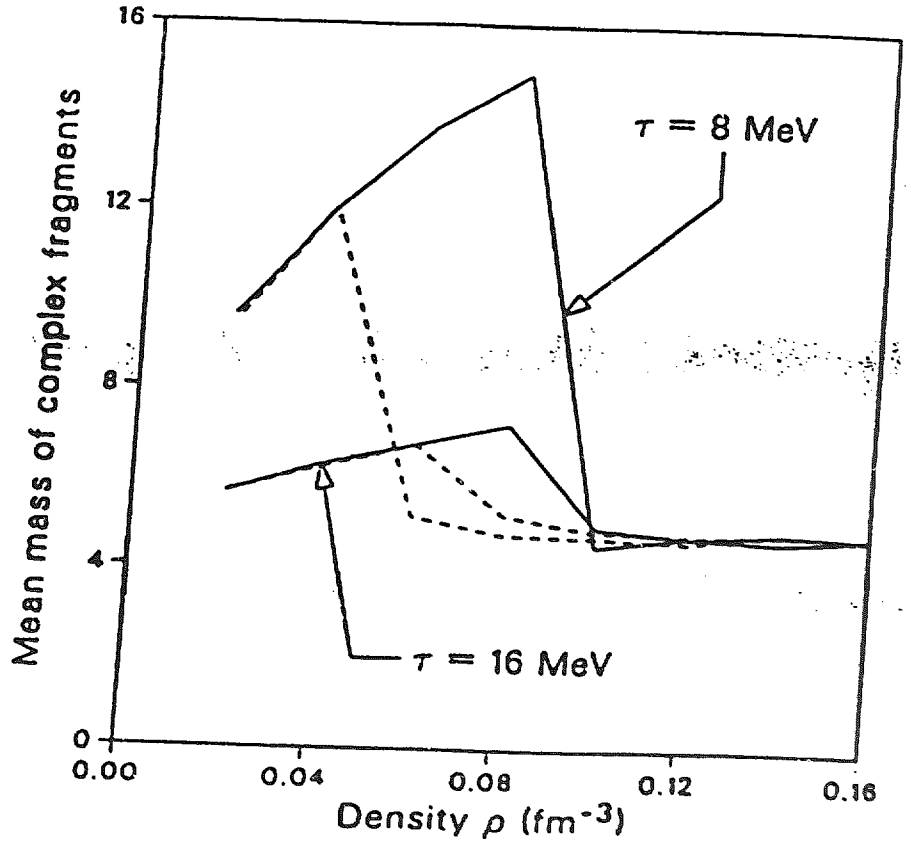


Fig 21

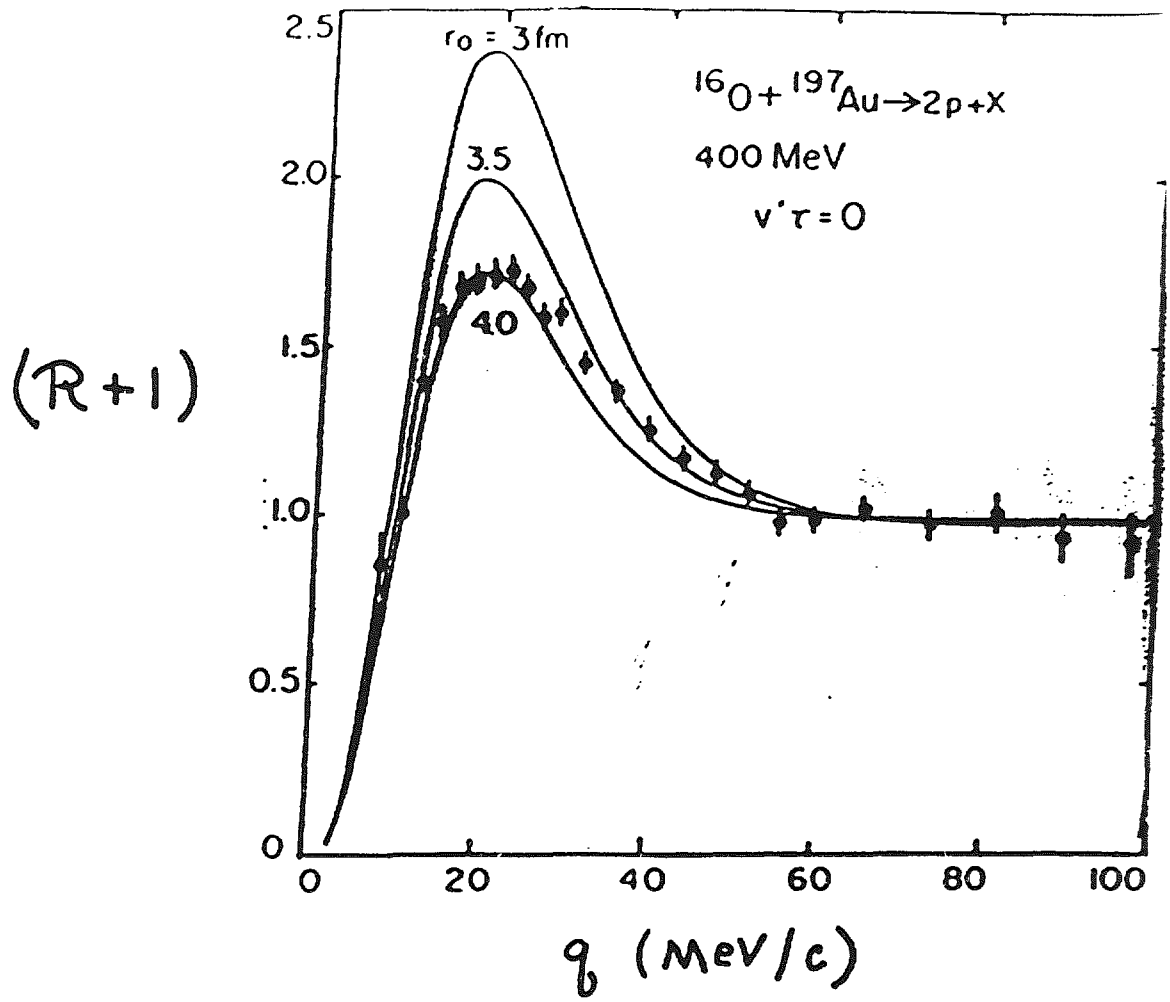
Transition State ?

‡ Entropy ?

‡ P. Siemens, Nature 305 410 (1985)

Fig 22

ORNL - MSU Phys. Rev Lett 51 1850 (1985)



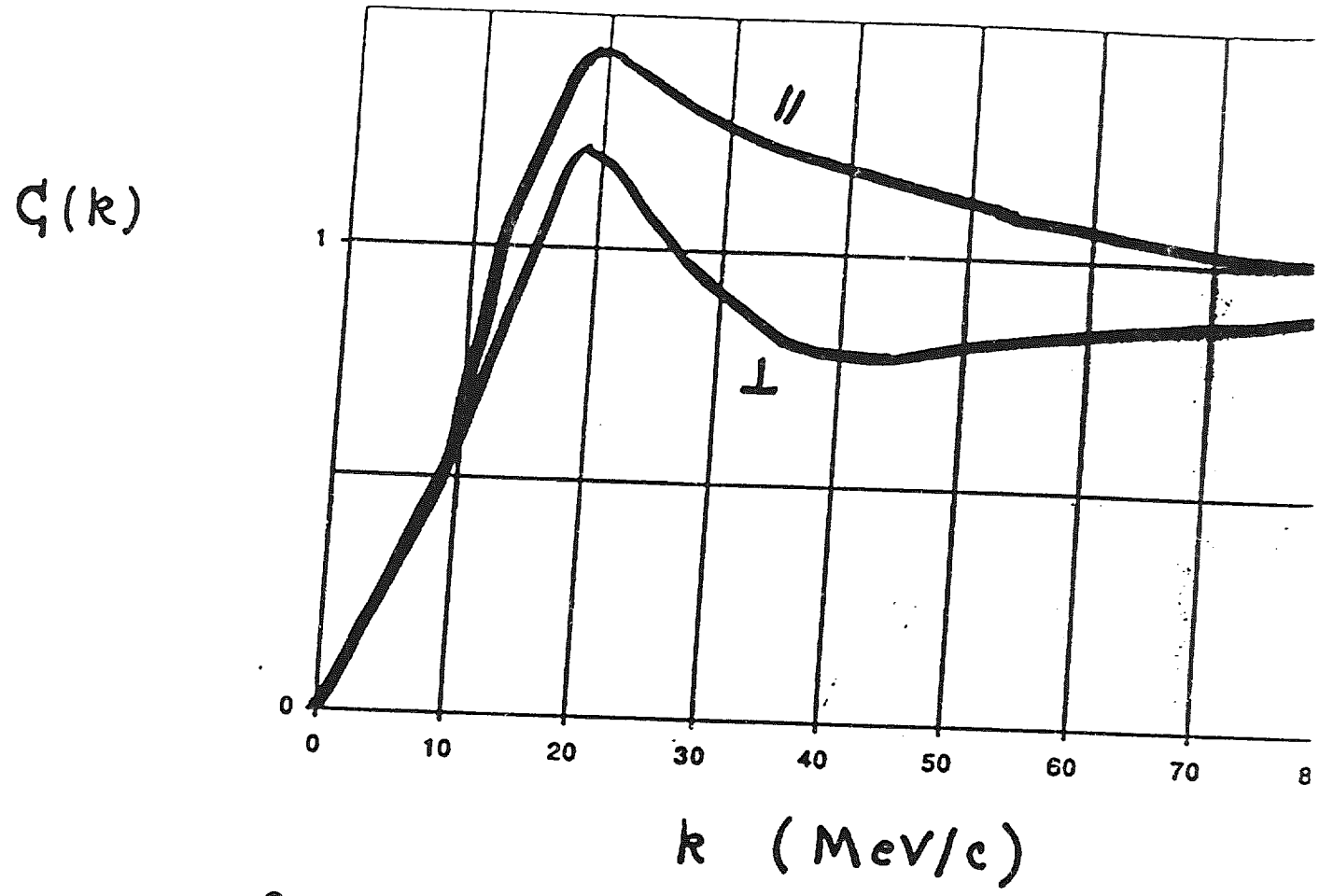
Koonin PL 70B '77

$$\sigma_0 \frac{d^6\sigma}{d^3p_1\, d^3p_2} = \frac{d^3\sigma}{d^3p_1} \frac{d^3\sigma}{d^3p_2} \left[R(p_1, p_2) + 1 \right]$$

singles spectra

Fig 23

Pratt & Tsang UT 1987



Gaussian Source : $R_\perp \sim 3$ fm

$R_{\parallel} \sim 12$ fm

p-p Correlations

$C(K,k)$ measure cm and rel. momenta of pair

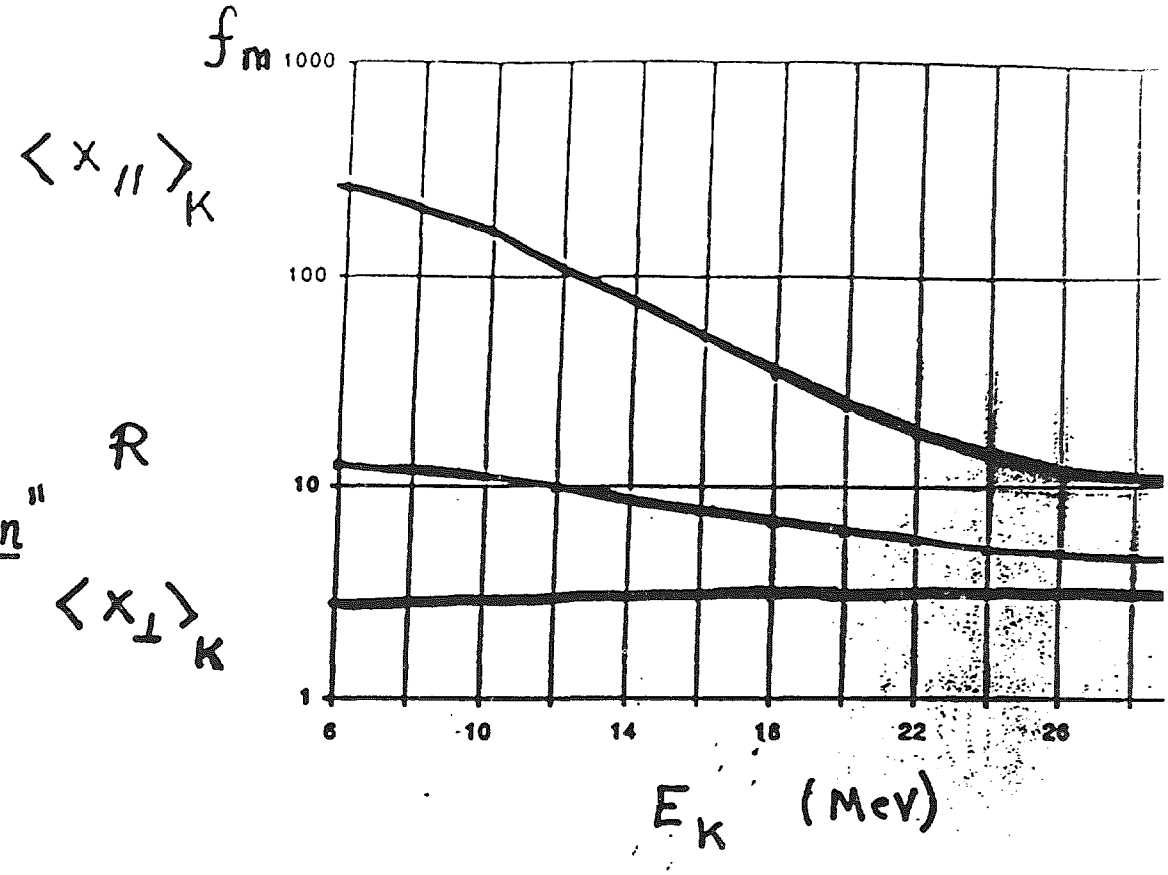
$F(K,r)$

Fig 24

Wigner Function

"Evaporation"

T = 10 MeV



"Exploding Sphere"

T = 10 MeV

$\beta = \frac{1}{3} \frac{r}{R}$

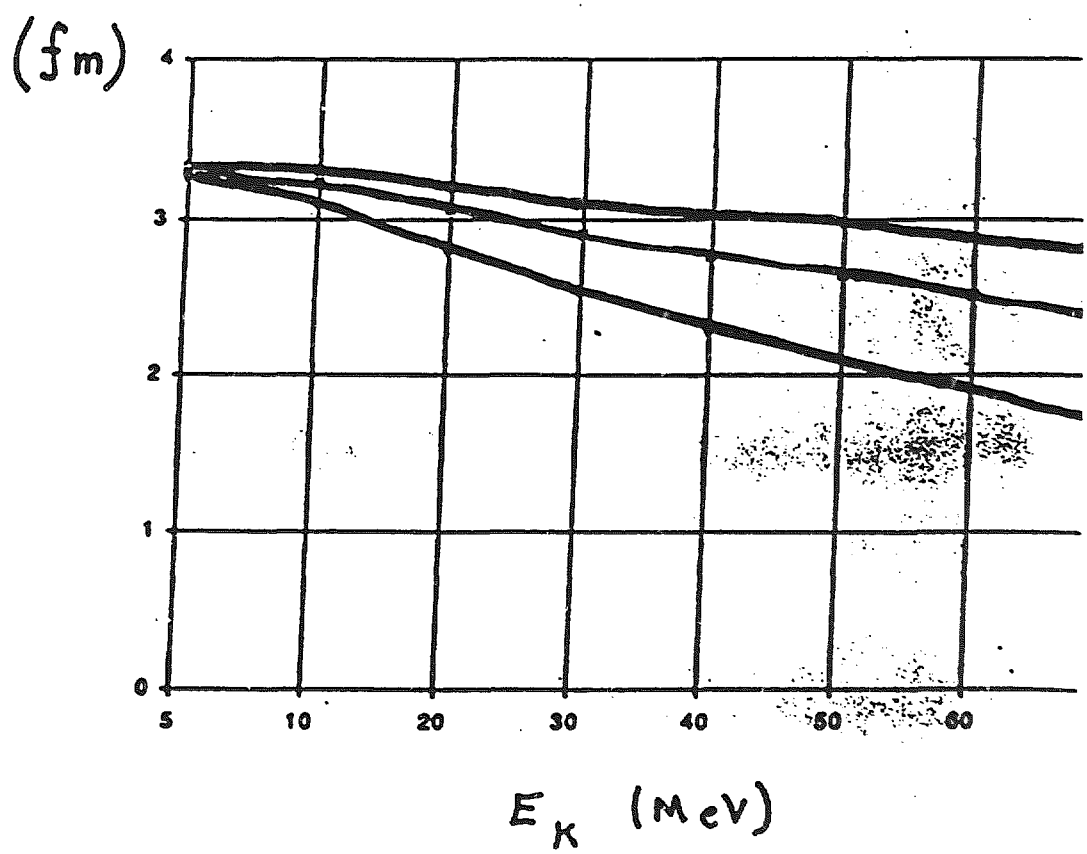


Fig 25

"Hanbury - Brown Twiss Correlations"

ORNL - MSU Collaboration

Awes	Chen
Obenshain	Pochodzalla
Plasil	Gelbke
Ferguson	Xu
Young	Lynch
ORNL	MSU

22.3 MeV per nucleon ^{32}S

Fig. 26

ORNL-DWG 88-16547

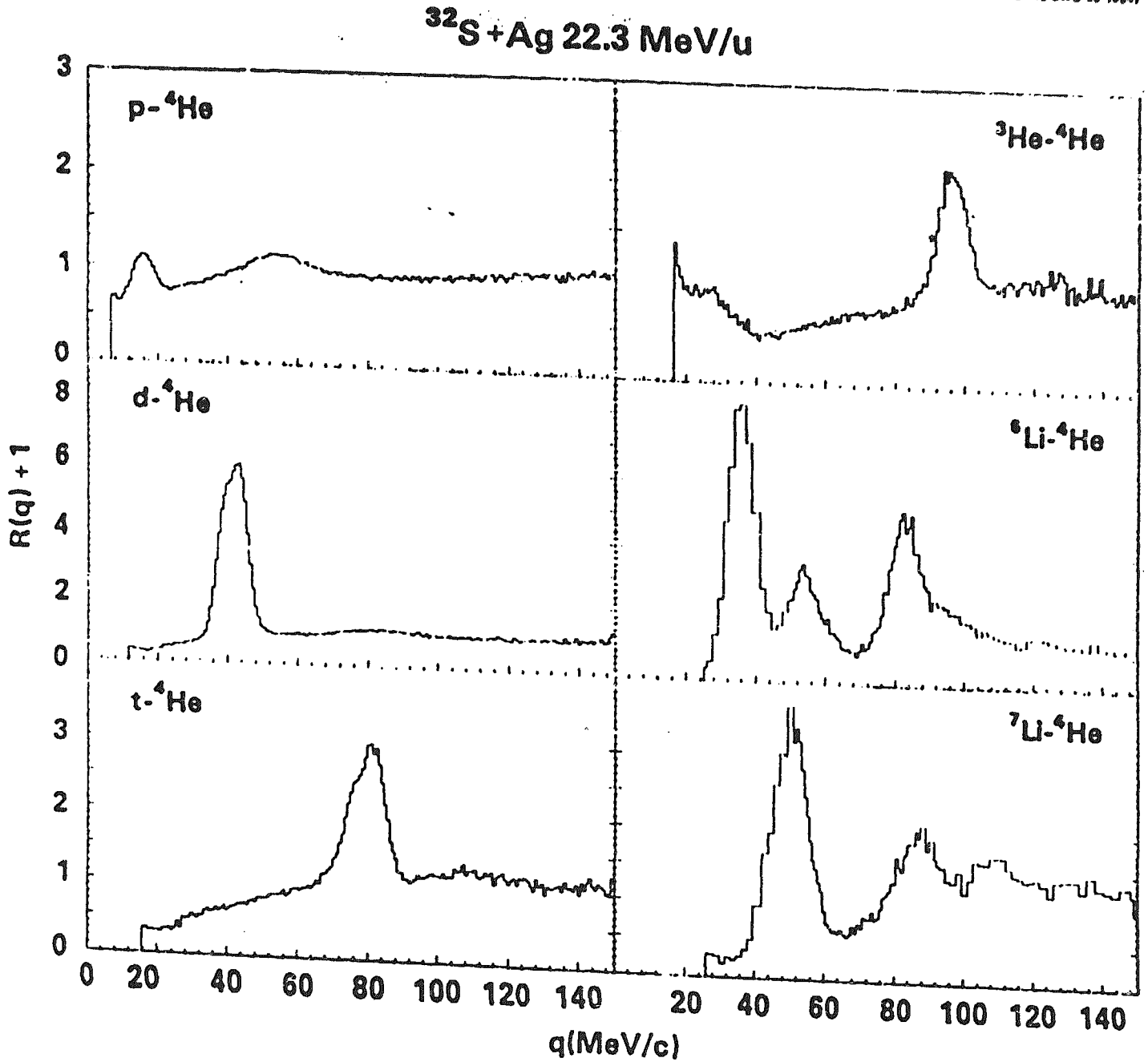
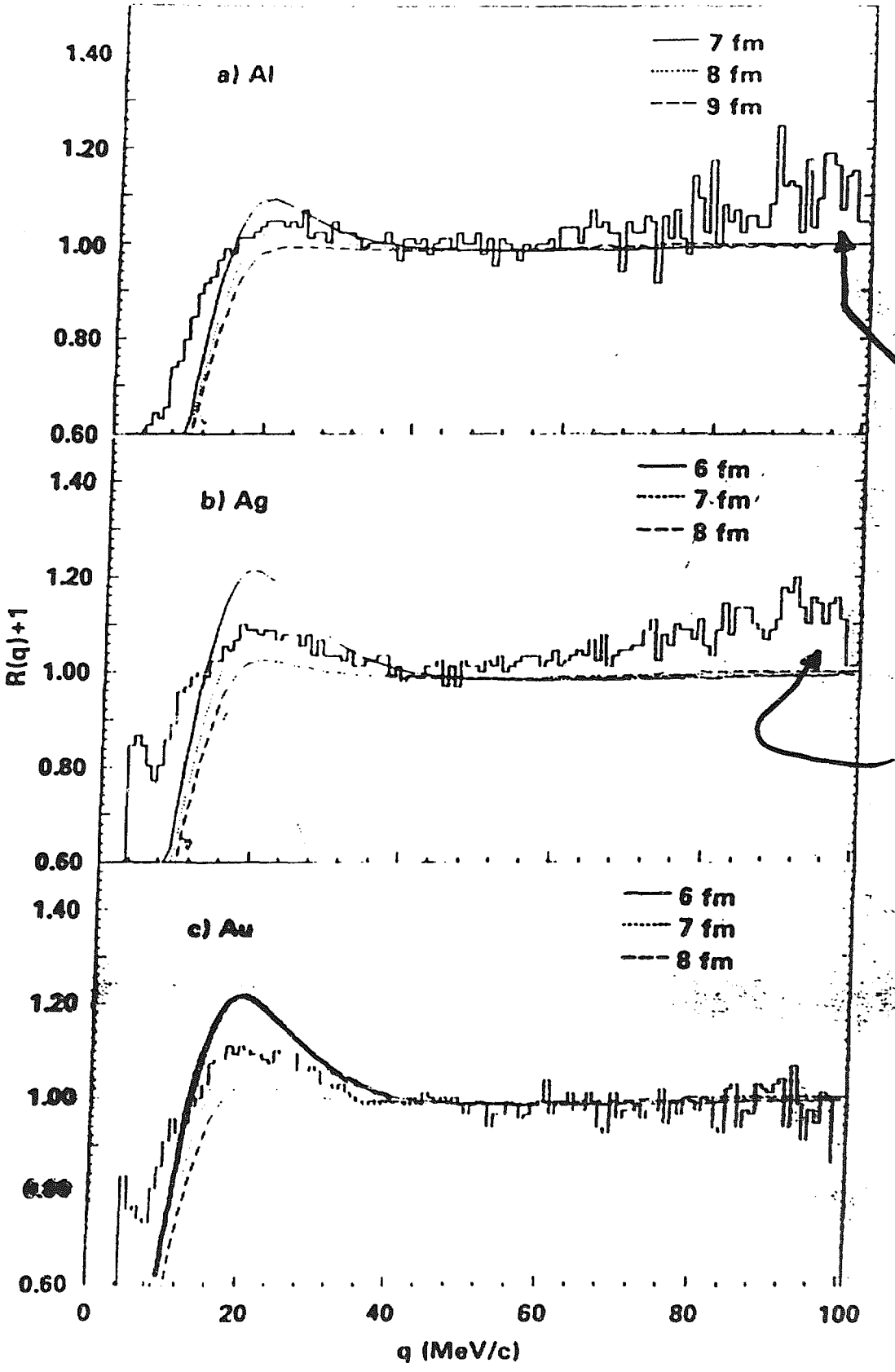


Fig 27

ORNL-DWG 86-16546

^{32}S 22.3 MeV/u p-p



Gas?

Fig 28

Mean Field with
2-body Collisions ?

Liquid-Gas Phase
transition ?

Fig 29