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NUCLEAR COLLISIONS AT INTERMEDIATE ENERGIES

DAVID K. SCOTT

Presented at
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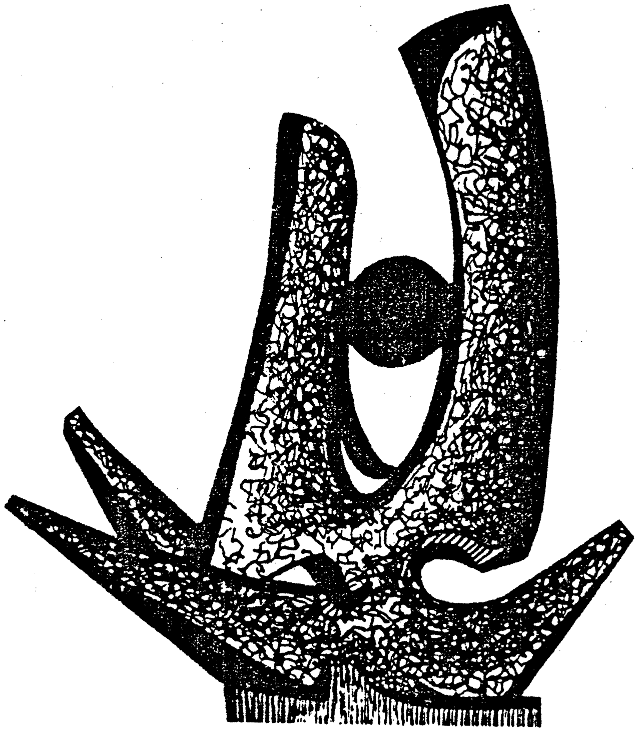

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Abstract: Two types of nuclear instability, which could play a role in intermediate energy heavy ion collisions, are discussed. One is a fast, mechanical instability leading to break-up of the system when the compressibility becomes negative, and the other is governed by a chemical instability between liquid and gaseous phases occurring on a slower time scale. Observable experimental consequences are suggested. Both types of behavior rely on a hydrodynamical description of nuclear collisions in which an initial heated and compressed zone undergoes an expansion and rarefaction. Compared to phase transitions of more exotic kinds, e.g. density isomeric states or, quark-gluon plasmas, the transitions we discuss are based on conventional aspects of nuclear behavior. They may, however, be useful in establishing whether hydrodynamical approaches and the time scales required for phase transitions are relevant for nuclear collisions.

1. Introduction

The study of nuclear collisions at intermediate energies, i.e. from approximately 20 to 200 MeV/nucleon, is now a burgeoning field$^{1-4)}$, as several accelerators dedicated to this energy regime have come into operation. From the accumulating body of experimental results it seems that the early prophecies for this field as one of transition and of complexity are being fulfilled. Both in experiment and in theory, the study of intermediate energy nuclear collisions bears a symbiotic relationship to its low and high energy hosts, drawing liberally from both. Our picture of the field is therefore at present a patchwork, in which the established phenomena at very low and at relativistic energies are interwoven. But if there is one striking characteristic of our present view of the intermediate energy domain, it is of paradox—highlighting the need for an eventual reconciliation of different approaches to the study of the nucleus. Thus the mean field, one-body dissipation and long mean free path limit of low energy heavy ion collisions must be merged with the two-body dissipation and short mean free path which are characteristic of nuclear hydrodynamical approaches at high energy. At energies of a few tens of MeV/nucleon the nucleus appears to exhibit a transparency of approximately 30% according to measurements of the reaction cross section,$^{1)}$ and yet another large fraction of the collisions ($\approx$20%) result in events with a high multiplicity of light fragments and no remnant of a forward going projectile - like fragment.$^{5)}$ The concept of transparency in peripheral collisions may have to be reconciled with that of opacity in central collisions.$^{3)}$ The degree of equilibration reached in intermediate energy collisions also presents something of an enigma, with both thermal equilibrium$^{2)}$ and single nucleon-nucleon collision models$^{1)}$

enjoying some measure of success. It is quite likely that the domain of intermediate energy collisions will ultimately call for novel theoretical approaches which synthesise the extreme viewpoints developed in the high and low energy limits. Recently some progress in this direction has been achieved.[6])

In this paper, I shall not attempt to review the large amount of data now available on intermediate energy collisions. Rather, I shall discuss some very recent developments in the field dealing with the production of complex fragments. The formation of these fragments may be influenced by two types of instability, which would open up an area of research unique to intermediate energy collisions. As in the examples discussed above these instabilities represent contrasting possibilities, namely a fast, mechanical instability leading to the break-up of a nuclear system into fragments, or a slower chemical instability involving a transition between gas and liquid phases.

In the next two sections these two types of instability are described along with possible observable consequences. The last section gives some perspective on the significance of these phenomena for the field of nuclear collisions in general.

2. Liquid-gas phase instabilities

One of the major goals of high energy nuclear collisions is the determination of the nuclear equation of state, i.e. the relationship between the variables pressure, density and temperature. Of particular interest are the possible phase transitions that could occur, when, for example, at high density and temperature, the nucleons in the nucleus may collapse into quarks and gluons.[7]) It is not known at present whether such new phases can be created in the laboratory; their description relies on the validity of hydrodynamical models of the collision. There is also a possibility for phase transitions of a less exotic kind to take place, the existence of which is based on established knowledge of nuclear behavior, but which if observed would help to substantiate the validity of a hydrodynamical description. One such transition could appear at low temperature and density as a liquid-gas phase instability, which would result in the disintegration of the nucleus into smaller fragments. Although frequent discussions of this phenomenon have appeared in the literature,[8]) its possible manifestation during the dynamical evolution of a heavy ion collision has only recently been considered.[9]) In the following, a simplified analytical treatment is presented to illustrate the basic ideas; more formal treatments can be found in refs. 8-14.

Consider the following parameterization of the energy per particle, E, in a nuclear system as a function of temperature, T, and density, ρ,

$$E = E_o + \frac{K}{18} \left(\frac{\rho-\rho_o}{\rho_o}\right)^2 + \frac{\pi^2}{4\varepsilon_F} T^2 \left(\frac{\rho_o}{\rho}\right)^{2/3}$$

comprised of the ground state binding energy per particle E_o, the compressional term containing the incompressibility K and a thermal contribution derived from the low temperature approximation for a Fermi gas; ε_F is the Fermi energy and the normal nuclear matter density of approximately 0.16 nucleons/fm. From the free energy F = E - TS, where the specific entropy $S = \frac{\pi^2}{2\varepsilon_F} T \left(\frac{\rho_o}{\rho}\right)^{2/3}$, we obtain,

$$F = E_o + \frac{K}{18}\left(\frac{\rho-\rho_o}{\rho_o}\right)^2 - \frac{\pi^2}{4\varepsilon_F} T^2 \left(\frac{\rho_o}{\rho}\right)^{2/3}.$$

The pressure as a function of ρ and T can be calculated from

$$P = \left(\frac{\partial F}{\partial V}\right)_T = \rho^2 \left(\frac{\partial F}{\partial \rho}\right)_T$$

The results of a more complete calculation are shown in Fig. 1,‡

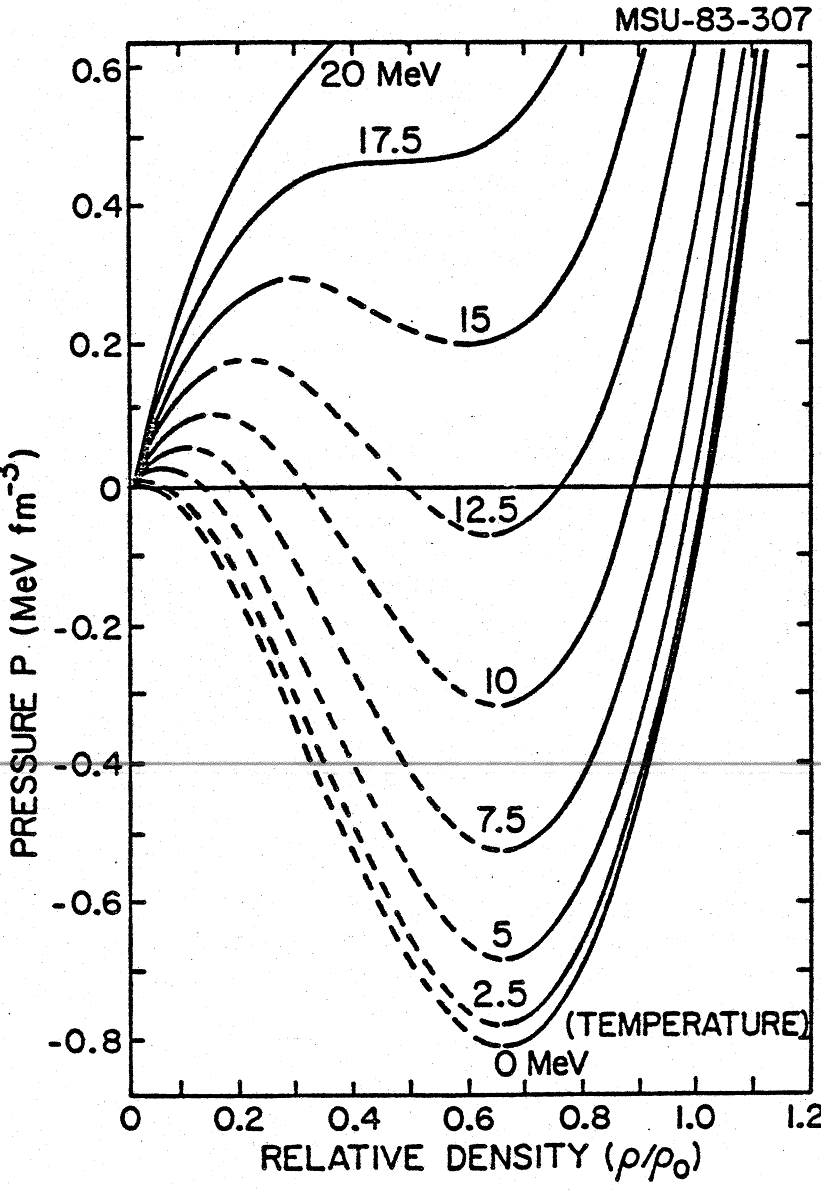

Fig. 1. The pressure P plotted versus the relative density ρ/ρ_o for various temperatures. For zero temperature, normal nuclear matter (with $\rho/\rho_o=1$) corresponds to a stable condition, where an increase of pressure leads to an increase in density and vice versa. This well-behaved part of the diagram, to the right of the dotted region, corresponds to the liquid phase. Another well behaved region lies at the far left, corresponding to a gas. The dashed parts indicate an unstable region where there is a mixture of liquid and gas phases. Above 17.5 MeV temperature where the isotherm has an inflection point, the nuclear system exists only in a gaseous phase.

where it can be seen that the equation of state has the form of a Van der Waal's system, for the simple reason that the nuclear and molecular systems are analogous; both are subject to short range attractive forces and very short range repulsions.

As in the Van der Waal's system, there exist liquid and gaseous phases. For the unphysical region (shown dashed in Fig. 1) where the slope of P vs ρ is negative (implying a negative incompressibility) a Maxwellian construction is employed, along which the liquid and gas phases coexist. This region of coexistence is illustrated more clearly in Fig. 2, which also shows that as the temperature increases, the apex of the coexistence region coincides with the inflection point of the critical temperature. This point corresponds to the condition,

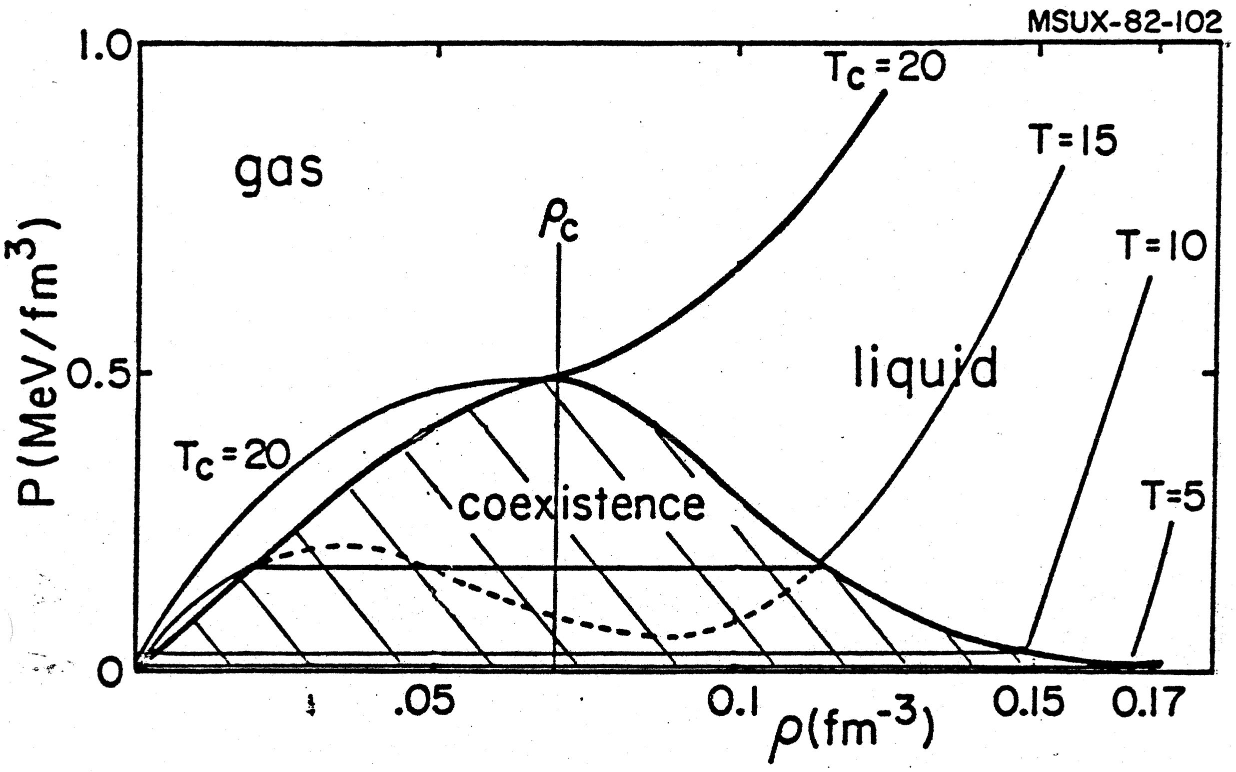

Fig. 2. Pressure versus density for fixed temperature is plotted. The solid curves indicate paths traversed by a system at fixed temperature. The liquid, gas and coexistence regions (hatched) are indicated. In this calculation, the critical temperature is T_c=20 MeV, with a critical density of 0.065 fm^{-3}.

$$\frac{\partial P}{\partial \rho} = \frac{\partial^2 P}{\partial \rho^2} = 0$$

A solution of the above analytical expressions with K ~ 210 MeV consistent with measurements of the monopole excitation, gives a result close to that obtained from a more detailed analysis, viz $T_c \simeq 18$ MeV and $\rho_c \sim 0.07$ nucleons fm^{-3}. For all higher temperatures only a gaseous phase exists.

Temperatures of this magnitude are reached in high energy heavy ion collisions where it is believed that a localized participant zone is created in thermal equilibrium. The subsequent emission of nucleons and light fragments have been quite well explained with models based on thermal and chemical equilibrium in a single gas phase.15) To determine the region of temperatures below 20 MeV we turn to Fig. 3, which shows the temperatures extracted from

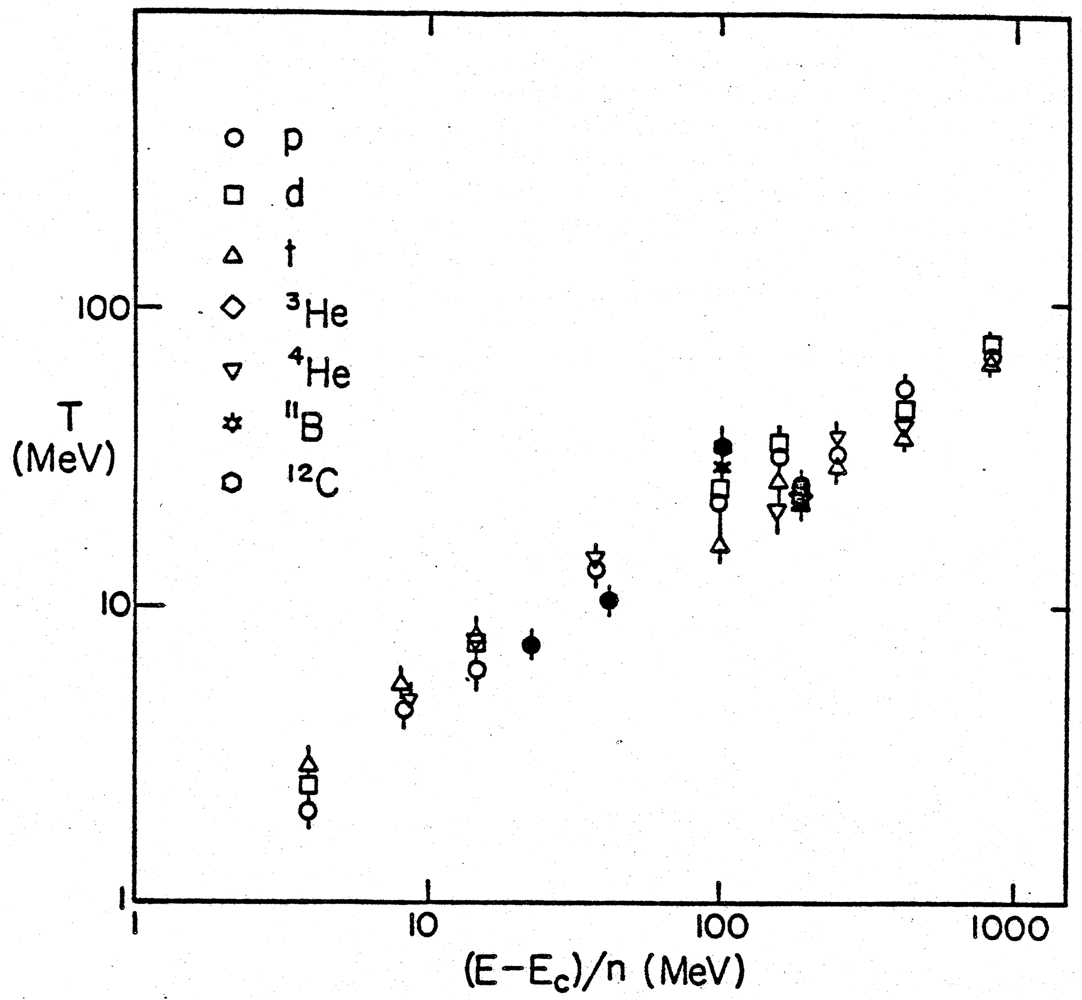

Fig. 3. Plot of temperatures as a function of incident energy per nucleon above the barrier, from a parameterization of the energy spectra of emitted light fragments with a localized moving source. Results are shown for different emitted fragments p, d, t, ^{3}He, ^{4}He, ^{11}B and ^{12}C in reactions induced by α, ^{16}O, ^{20}Ne and ^{40}Ar. (See refs. 16 and 17 for details.)

a study of emitted light fragments ranging from protons to ^{12}C in reactions induced by incident projectiles from α particles to Ar Argon.[16,17]) The values of temperature were derived by fitting the spectra of the light particles by a "moving source model", characterized typically by a velocity half the projectile velocity, i.e. a source of intermediate rapidity such as would be expected if projectile and target contribute roughly equally number of nucleons to the formation of the hot zone. At high energies of several hundred MeV/nucleon and above direct evidence for the existence and size of such a localized zone is yielded by experiments on two-particle interferomtery.[18]) No such convincing proof is yet available at intermediate and low energies, but we shall proceed to make use of the results of Fig. 3 for the temperature as a function of incident energy.

We note, however, that the trend of temperatures in Fig. 3 is roughly that expected for a Fermi system composed of equal numbers of projectile and target nucleons. Thus if we write the expression for temperature in a Fermi system as $E^* = T^2/16$, where

E^* is the excitation energy per particle and the factor 1/16 comes from the level density parameter, then the result $E^* = 1/4\ (E_L/A)$ follows, where E_L/A is the incident laboratory energy per particle. Then $T = 2\sqrt{E_L/A}$; for $T \simeq 20$ MeV we obtain $E_L/A = 100$ MeV/nucleon in agreement with the experimental result. Temperatures below the critical value of 18 MeV are therefore appropriate to collisions below 100 MeV/nucleon, placing the observation of the liquid-gas phase instability in the intermediate energy regime.

In a recent paper$^{16)}$ the trends of emitted light particles (p,d,t, ^{3}He, α) were studied. For each reaction a component in the energy spectra was attributed to emission from a localized participant source of velocity intermediate between those of projectile and target and the associated temperatures were deduced as in Fig. 3. The integrated cross sections from the curves are

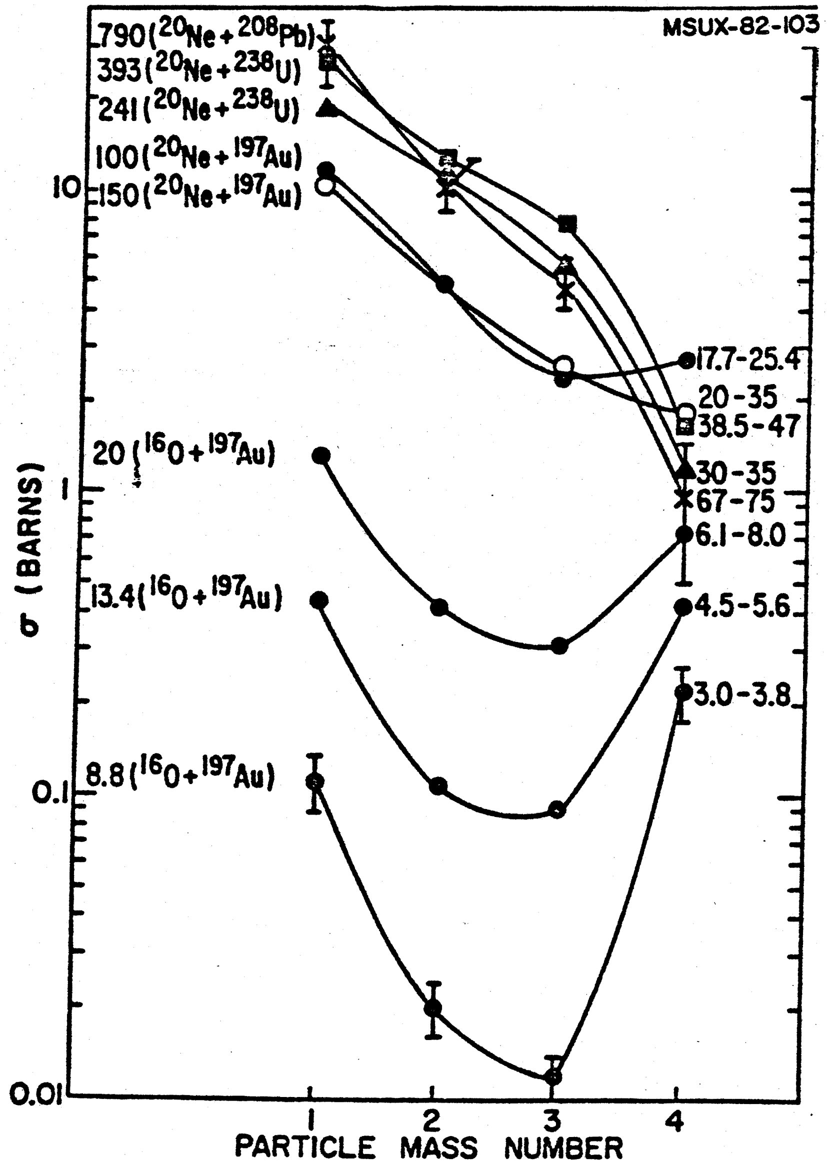

Fig. 4. Cross sections for different fragment masses are plotted for a range of incident energies (shown on the left) and equivalent temperatures (right). Error bars are indicated for highest (X) and lowest (●) incident energies. Of particular interest is the monotonic decrease of yield with fragment mass at high incident energies, and the reversal of this trend at energies below 100 MeV/nucleon.

labeled by the incident energy, projectile and target on the left. Temperatures are labeled on the right. In each case a range of temperatures is indicated accommodating the limits for fitting spectra of different emitted particles.

At high incident energies, corresponding to high temperatures, the yield falls off monotonically as a function of particle mass. This behavior is expected for emission of clusters from a high temperature, single gaseous phase where the composite production cross section can be related to a power of the nucleon cross section. This result is common to both the coalescence and thermal models.15) In the region of $E_{inc} \approx 100$ MeV/u corresponding to $T \approx 20$ MeV, the distribution flattens and at still lower temperatures the trend reverses so that the alpha particle yield exceeds that of lighter particles. It is tempting to attribute this enhanced cluster formation at temperatures below 20 MeV to the onset of the liquid-gas instability we have discussed but a more convincing demonstration must await data on the production of heavier clusters. We should also point out that a recent detailed study8) of the liquid-gas phase instability in finite nuclear systems, as opposed to infinite nuclear matter, implies that the critical temperature could then be lowered to a value in the range 8-13 MeV.

3. Mechanical instabilities

Another type of instability which could take place on a faster time scale than the liquid-gas phase transition has also been discussed recently.19) This concerns a mechanical instability, in which the compressibility of the nuclear system, $k = \rho\frac{\partial P}{\partial \rho}$, becomes negative. Such a region is easily identified in Fig. 1, but is more clearly defined in Fig. 5, which shows the energy per nucleon as a function of density. Here the region labelled "unstable zone", defines where nuclear matter becomes dynamically unstable. The authors of ref. 19 argue that the occurrence of nuclear fragmentation as a dominant reaction process depends on whether the system enters this unstable region. Since this region is defined by a boundary of lower than normal nuclear matter density, it is necessary to consider how it can be reached, given that we must always start with nuclear system prepared at normal or greater than normal density.

Initially a nuclear reaction carries the system from the ground state to some point with higher internal energy. If the energy is transferred by a proton, it is plausible to assume that no significant conpression takes place. On Fig. 5 one therefore moves vertically upwards on the diagram from the minimum at normal nuclear density, requiring an injection of approximately 10 MeV per particle. On the other hand for heavy ion collisions we expect some compression to occur, so that the system is initially prepared at a point to the right of the minimum at normal density. From this condition it is assumed that the nuclear system will expand along an isotrope until a point of equal internal energy is reached on the left. The justification for an expansion at constant entropy is based on cascade calculations,20) which indicate that little dissipation takes place; other evidence comes from our knowledge of the monopole vibration, which has a damping width much smaller than its excitation.21) In Fig. 5 the region of appropriate initial conditions which will provide access to the fragmentation zone is defined by the dashed boundary of the shaded region labelled "overstressed zone". For example a compression of 1.4 over normal density is

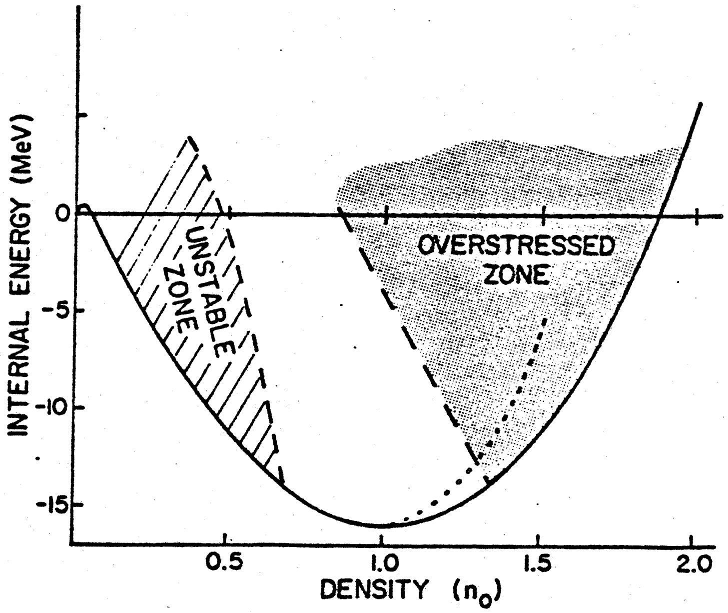

Fig. 5. The internal excitation energy per nucleon is shown as a function of relative density. The shaded portion on the left, labelled "unstable zone", defines the region of negative incompressibility. The shaded area on the right defines the overstressed zone from which a nuclear system will be able to reach the fragmentation zone through an isentropic expansion. The dotted locus extending into the overstressed zone indicates the trajectory expected from theoretical calculations of heavy ion collisions.

predicted in TDHF calculations at 10 MeV/nucleon (see the dashed line to the left of the $S = 0$ isentrope in Fig. 5) and if it is assumed that all of this excitation energy is thermalised the threshold for fragmentation would be lowered to few MeV/nucleon. The corresponding incident energy in the laboratory, assuming again equal contributions from target and projectile, would be in the region of 12-20 MeV/nucleon. Above this threshold the system will always come apart in fragments. An observation of the onset of fragmentation might therefore provide a means of inferring the density at which thermalization takes place; the energy threshold for fragmentation should be an increasing function of the initial density.

This type of instability is quite different from the liquid-gas instability, which is a first order transition applicable to processes that occur slowly enough for an equilibrium to be established across the phase boundary. According to the picture of expansion and rarefaction of the initial compressed zone on a time scale commensurate with the frequency of the monopole vibration, this time can be estimated from the typical excitation energy in a medium weight nucleus,[21] $E \approx \hbar\omega \simeq 15$ MeV, resulting in an expansion time of the order 10^{-22} sec. At present it is not clear if the liquid-gas phase instability can be established on such a short time scale.

Although evidence for this fast mechanical instability has not yet been demonstrated, it is of interest to consider the type of experimental data which may be relevant. It is well known that in high energy proton-induced spallation the cross section for fragment production increases dramatically up to energies of a few GeV, followed by a levelling off in the cross section. An example[22]) is illustrated in Fig. 6 for p + Ag

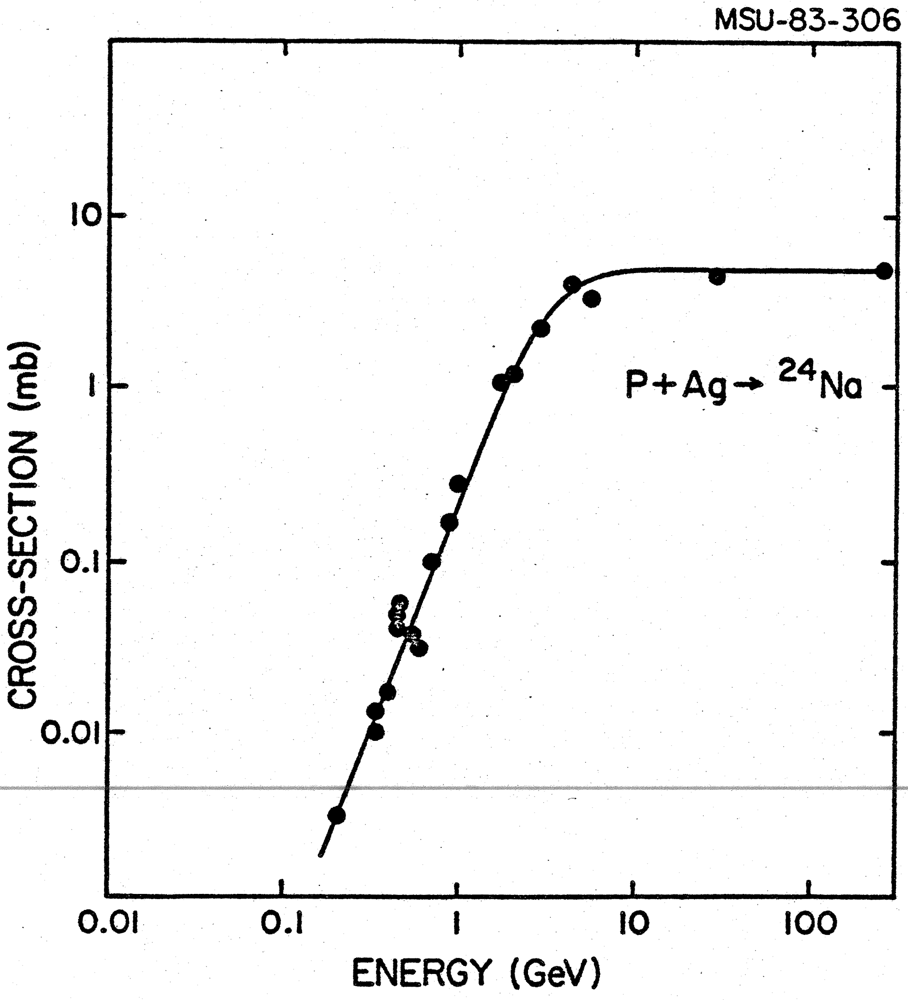

Fig. 6. The cross section for the production of ^{24}Na in spallation reactions induced by protons on Ag as a function of incident energy. Following a rapid rise, the cross section saturates at energies above 1 GeV.

leading to ^{24}Na. The saturation is usually attributed to a limitation of the energy deposition in the nucleus when it becomes transparent to protons of a few GeV. On the other hand the behavior may be related to the onset of fragmentation when the system reaches the overstressed region.[19]) For the system proton on Ag with about 108 nucleons, our previous discussion would imply that about 1 GeV of energy is necessary. Of clear interest here would be a comparison with heavy ion induced fragmentation in order to discover if the saturation sets in at a lower energy in the presence of some compression.

We must point out that a recent investigation of the variation of cross sections for cluster production in very high energy proton-nucleus collisions has been interpreted in terms of critical fluctuations of the nuclear system in the presence of a liquid-gas instability.23,24) The distribution obeys a power law form, $\sigma\ \alpha\ A^{-k}$ where A is the fragment mass and k has a value of approximately 2.64. Such a power law is expected for condensation in macroscopic systems near the critical temperature as formulated in the droplet model of Fisher.25)

It is possible that both types of instability may play a role in nuclear collisions; a detailed comparison of light and heavy ion induced reactions may help to clarify the contributions from different mechanisms.

4. Conclusions and outlook

In this paper we have drawn attention to two types of instability in nuclear systems - a fast mechanical instability and a slower chemical instability. Their manifestation relies on a hydrodynamical description of the collision, in which the nuclear system, or a part of it, undergoes initial compression and heating, followed by an expansion which reduces the temperature and density. During the expansion the system may encounter the conditions of temperature and density appropriate for the instabilities to develop. It is conjectured that observable experimental consequences may be found in the production cross sections of complex fragments. At present there are suggestive hints of behavior that could be due to the instabilities.

If the observable consequences can be predicted in detail, then such experiments are of some importance in that they give information pertinent to the equation of state of nuclear matter. At present many questions remain—whether, for example, there is time for the instabilities to develop and whether any trace of the effects will persist in the final distribution of fragments observed in the detector. Of course many of these criticisms can also be levelled at attempts to study the equation of state at greater than normal density where phase transitions into new states of matter in the form of density isomers and quark plasmas are theoretically possible. The instabilities discussed in this paper are based on more conventional knowledge of nuclear properties but may nevertheless provide insight into experimental searches for more exotic phenomena. Since the energy domain appropriate for the transitions to take place lies between 20 and 200 MeV/nucleon, the experimental detection of such phase transitions belongs to the field of intermediate energy nuclear collisions. This fledgling field may, therefore, be able to repay some of the debt owed to its high and low energy counterparts, from which many concepts were initially borrowed.

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ǂ For clarity some of the illustrations in this paper have been redrawn from originals. Reference should be made to the original literature for precise figures.

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