Title
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Publication Date
1982-04-01

LBL-14371

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Presented at the International Conference on Selected Aspects of Heavy Ion Reactions, Saclay, France, May 3-7, 1982

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April 1982

NUCLEAR SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

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LBL-14371

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This work was supported in part by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

NUCLEAR DISINTEGRATION IN RELATIVISTIC HEAVY ION COLLISIONS*

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Abstract: The breakdown of the participant spectator model for central relativistic nuclear collisions is discussed and a different picture of a hot spot followed by a target explosion is suggested to be more consistent with the data.

1. Introduction

Since the days of the earliest Bevalac experiments one of the main goals in the study of relativistic nuclear collisions has been the determination of the equation of state of nuclear matter, particularly at densities much larger than the nuclear density. Over this period attempts have been made to observe collective phenomena that would justify the use of terms like density, pressure, temperature, and phase transition: in other words, terms associated with states in equilibrium.

In 1976, the nuclear fireball model[1)] was formulated, predicting not only the emission of nucleons but also the production of clusters like deuterons, tritons, etc., which were assumed to be in chemical equilibrium. The geometry for a given impact parameter defined how many particles would interact with one another, thus being called the participants, and how many particles in each nucleus would miss a collision, thus being called the spectators. For small projectiles and large target nuclei and rather central collisions it means that the projectile would sweep out a cylinder-like part of the target nucleus and form with it a nuclear or hadronic fireball. Since the geometry defines the number of participants in the fireball, its temperature and velocity are well defined and only in the cluster production is there a parametrization, namely of the freeze out density at which the chemical activity stops.

The only model with a direct link to the equation of state of nuclear matter is the hydrodynamical model,[2)] which treats the nuclear collision as that of two liquids. A local thermal equilibrium is always established. This model is based on small mean free paths of the nuclear constituents. A somewhat orthogonal view is taken in the intranuclear cascade model,[3)] where nuclear collisions are treated as cascades of nucleon-nucleon collisions with cross sections taken from nucleon-nucleon scattering data. Both models predict, in a central collision, a fast energy dissipation in the early diving stage of the projectile into the target nucleus. In the final state both models show total incident energy largely dispersed over the whole target nucleus. However, in a quantitative comparison of the data with the results of intranuclear cascade calculations the measured 90° double differential cross section seems to be flatter than the calculation. The data apparently have a higher temperature than the cascade predicts.

This report will suggest and discuss a picture of the reaction mechanism where the light projectile (e.g. Ne) "gets stopped" very early in the large target nucleus (e.g. Au or U) forming a small fireball at approximately half the beam rapidity, which decays inside the target nucleus, heating it up and causing the whole system to expand. The expansion cools the system and big clusters can condense out if the total energy and thus entropy in the system is not too high to prevent it. Such a qualitative picture of a reaction mechanism emerges when we consider the information obtained about relativistic nuclear collisions from measurements of the remnants of a large target nucleus struck by a smaller projectile (Ne + Au) and relate it to the complementary information from earlier measurements[4] of fast light reaction products. In this sense we are reviving aspects of earlier proton-nucleus measurements[6] and comparing them to more complex correlation data.

2. Experiments

Most of the data discussed here have been collected with the system depicted in fig. 1. It consists of three subsystems, the vacuum-scattering chamber with a diameter of 1 meter and wall thickness of 3 mm of Al, the 80-fold plastic scintillator array around the scattering chamber and the Plastic Wall covering the forward angles from 2.5° to 9°. Inside the scattering chamber in earlier measurements of π^+, p, d, t data[4] a Si-Ge telescope was used. Later for the measurements of very slow fragments[7] a single gas ionization chamber with Si-E detectors and an array of 5 Si detectors in coincidence were used. Finally, the pictured system of parallel-plate avalanche counters, silicon arrays, and 4 ΔE-E telescopes was mounted, a total of 48 telescopes inside the chamber[8]. This enabled us to study all the various correlations between the slow fragments and between the slow and fast fragments, as measured in the 80 scintillator multiplicity array outside the vacuum chamber. Special efforts were made to achieve the lowest possible energy cutoff for the heavy fragments. This was done by building start detectors for the TOF system with a

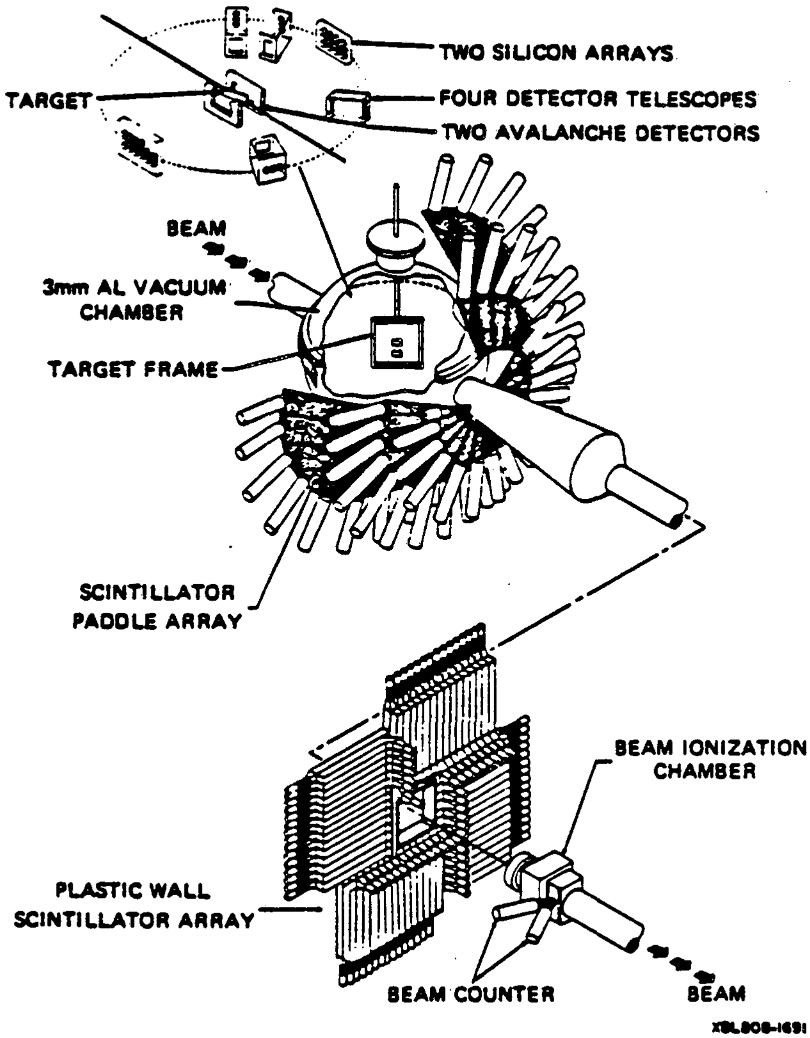

Fig. 1 Experimental setup[2,7,8] used to measure correlations among slow fragments and their associated fast particles.

3 thickness of only 150 μg cm^{-2}. The multiplicity array yields data on the charged particle multiplicity associated with a fragment measured inside the scattering chamber. Thus the charged particle multiplicity associated with the trigger fragment is a characterization of the event. The energy of the charged particles has to be larger than 25 MeV/n in order to penetrate the 3 mm Al chamber wall and fire the plastic scintillators.

3. Stopping of the Projectile

A reaction can be crudely described by the projectile's energy loss. A compound nucleus reaction shows total momentum and full energy transfer. Other reactions might be more peripheral in nature and involve only a small transfer of energy and momentum. At low bombarding energies, around 5 MeV/u, the reaction mechanisms are fairly well established. Over a larger range of incident energies, however, the mechanism of a central collision might change its character completely. At low energies around 5 MeV/u the compound nucleus formation is the reaction where the projectile "gets stopped" in the target nucleus forming a new system with a specific excitation energy and angular momentum. This system decays via evaporation and/or fission. At low energies two fission channels are operating, in a central collision the compound nucleus dominantly decaying via fission and for very peripheral collisions the target nucleus undergoing fission after being excited in inelastic collisions (e.g. Coulomb fission). At energies beyond 15 MeV/u the fusion-fission in a central collision decreases until at high incident energies only the peripheral reaction can proceed through the fission channel. Thus, if one wants to study the central collisions over a large range of energies, some other channel has to be found that is clearly related to a small impact parameter. It is then of interest to find out what happens to the target nucleus in a central collision at high energies.

Looking to the opposite end of the mass spectrum of emitted particles one can study the proton and deuteron emission in a reaction. This has been done extensively since 1975 in single particle inclusive measurements. More recently, coincidence experiments have directly measured the multiplicities of these light fragments.[4] The multiplicity can give information on the amount of energy dissipated inside the target nucleus. Using the results of an experiment obtained with the facility described,[4] the light particle emission will be discussed to find out how it agrees with the participant spectator idea mentioned in the introduction.

The charged particle multiplicity associated with the observation of a proton at 90° is shown in Fig. 2 plotted versus the average number of participants, as measured in various projectile-target combinations.[4] As the incident energy is increased the charged particle multiplicity is increasing way beyond the participant number. What is measured in this experiment is more than the participants, and a source other than the fireball has to be found to produce many particles beyond 25 MeV kinetic energy (proton equivalent). If one looks in a different way at the charged particle multiplicity associated with the 90° proton, namely as a function of total incident kinetic energy for a heavy target, then, as shown in Fig. 3, one observes a continuous rise up to 42 GeV. Even when changing the trigger particle from a proton to a deuteron or triton or a slow fragment like C, O, or Ne, the total kinetic energy is determining the charged particle multiplicity as shown in Fig. 4 for 4 and 8 GeV ^{4}He and ^{20}Ne on Au.[7] Such a strong dependence, independent of projectile size, rules out totally the simple geometry of the fireball[1] and related models,[5] which assume a clean-cut geometry. This rise of the associated charged particle multiplicity as a function of incident total energy leads one to conclude that the target nucleus gets blown apart more and more the higher the incident energy.

Another important piece of information on the reaction mechanism is contained in the single particle inclusive spectra of high multiplicity events.[9] In fig. 5 it is shown that at 2.1 GeV/u ^{20}Ne + U apparent temperatures of up to 150 MeV have been observed, much higher than the fireball model predictions of

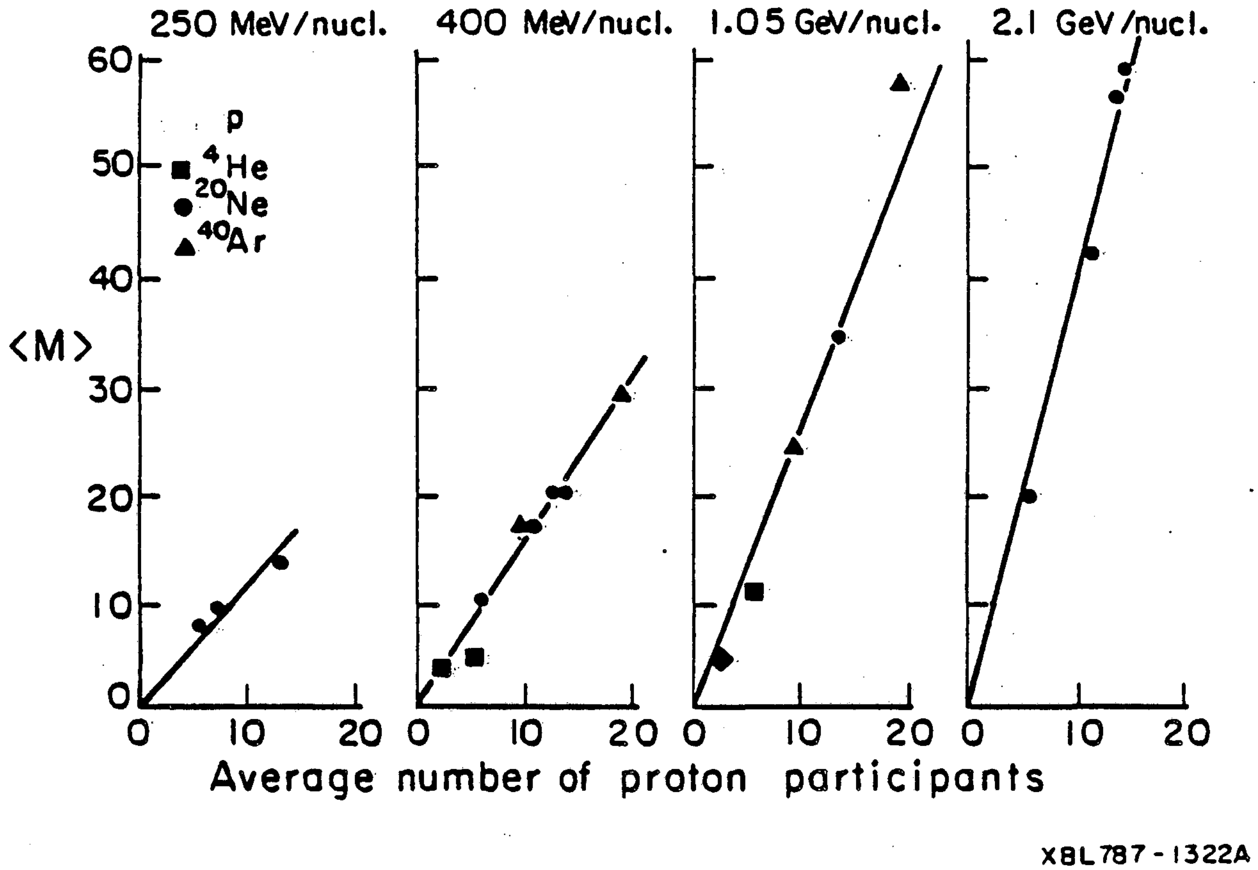

Fig. 2 Charged particle multiplicities associated with the detection of a 20-200 MeV proton at 90° in the lab system, plotted versus the average number of participants.

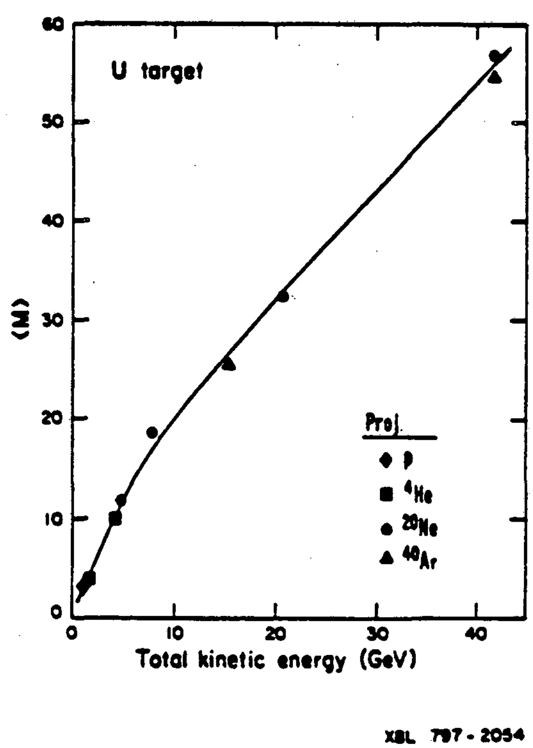

Fig. 3 Charged particle multiplicity associated with the detection of a 20-200 MeV proton from the bombardment of a U target with p, ^{4}He, ^{20}Ne, ^{40}Ar beams plotted versus the full beam energy.

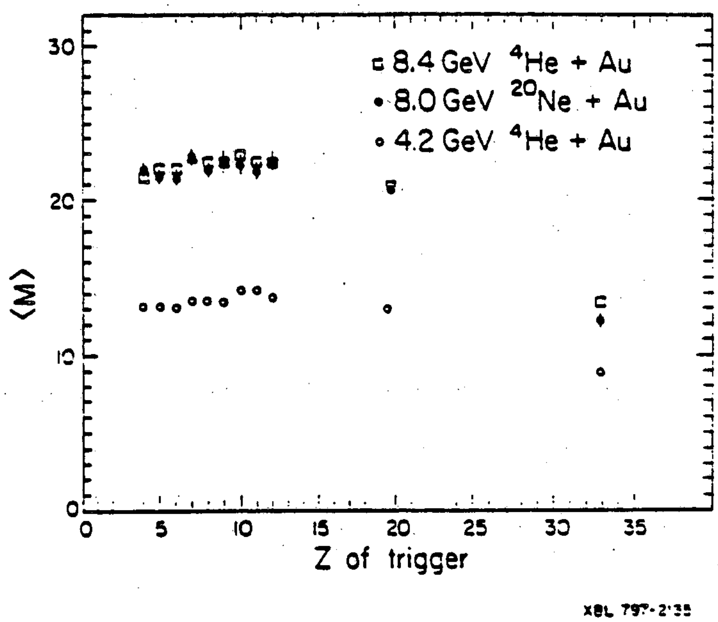

Fig. 4 Charged particle multiplicity associated with the detection of low energy fragments with $3 < Z \leqslant 26$.

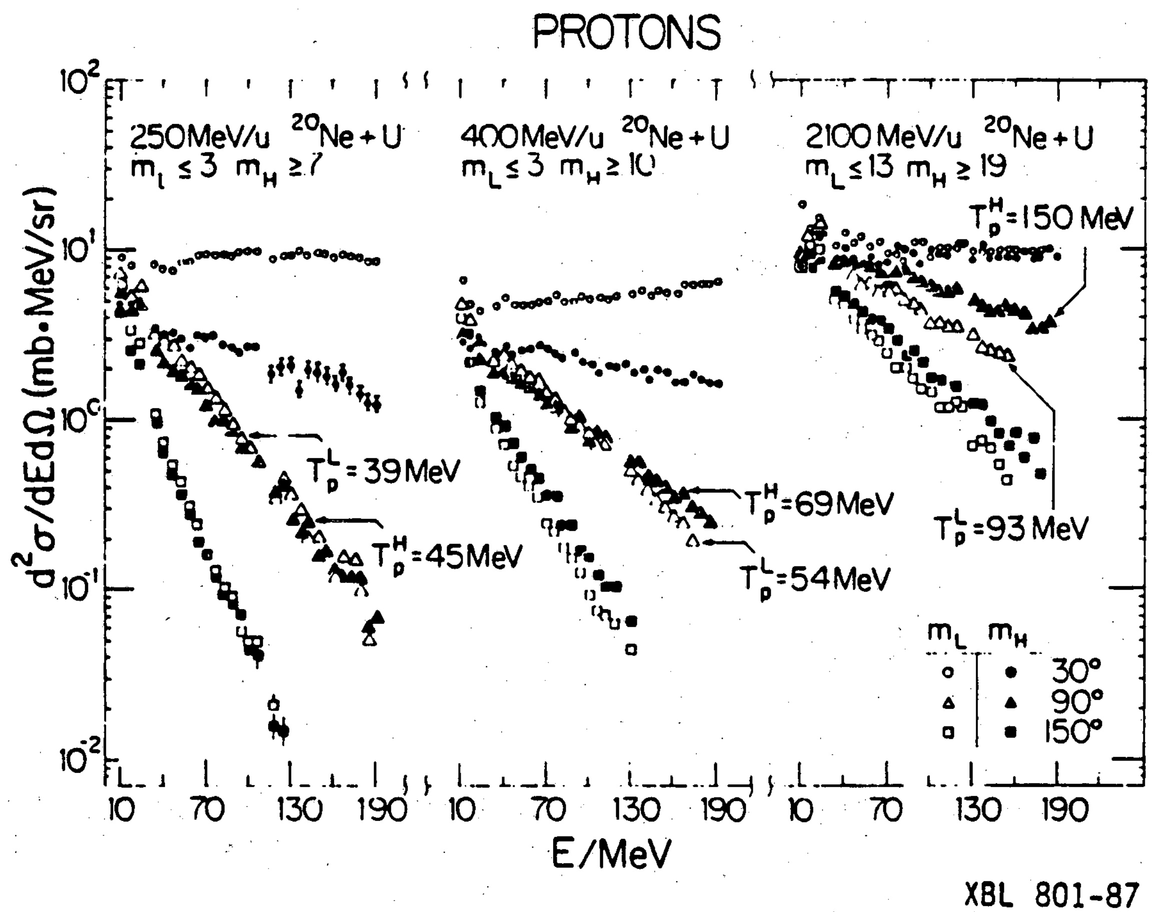

Fig. 5 Double differential cross section of protons from high multiplicity reactions.

~92 MeV. For a thermal system this is only possible if the available energy is dissipated among fewer constituents in the fireball, i.e. if the number of degrees of freedom is much smaller than the fireball model predicts. One is led to switch from the standard fireball geometry (participant-spectator geometry) to that of a small hot spot. formed by an equal number of nucleons from the target and the projectile. A fireball type calculation for such a hot spot yields temperatures of up to 109 MeV,[5] still below those observed. To produce the high observed temperatures requires a collective recoil of the whole nucleus taking up momentum of the projectile and dissipating more kinetic energy than before in the hot spot volume. This is analogous to the idea of forging, where the anvil makes it possible to dissipate all the kinetic energy of the hammer in the small volume of the forged piece. W. Swiatecki[11] has discussed nuclei responding like a viscous liquid to slow perturbations and like an elastic solid to fast processes, the "silly putty" analogy. We may be observing this latter behaviour here.

We have now made two observations that seem to contradict each other.

a) The total kinetic energy of the projectile determines how many fast particles can be observed and one concludes that at high energies more nucleons participate in the collision process than is predicted by the fireball models.

b) The slope of the spectra indicate a higher temperature than calculated in the participant-spectator geometry with the fireball chemistry. One wants to conclude that the emitting system is smaller than the standard fireball, actually like a hot spot on the target nucleus.

One can resolve this puzzle by considering b) to be the experimental proof for a primary reaction zone (hot spot) in the heavy target nucleus where the projectile deposits all its energy. Particles are emitted from this primary interaction zone, some of them penetrating into the cold remainder of the target nucleus. A large fraction of these emitted particles can reach a detector at large angles without having to penetrate the cold target matter and exhibit the features of emission from the hot spot. At forward angles, for small impact parameters, the emerging particles must go through the rest of the target nucleus, being attenuated according to their mean free path, and reaching the detector with less energy than they started out with. The energy loss of the particles emitted into the cold target remnant heats it up and leads to the tremendous increase of charged particle multiplicity due to cascading effects.

4. Expansion and Cooling

In the proposed picture of a compressed hot spot, thermalization is indicated when the emission of fast light clusters is studied. The thermal assumption implies a relationship between the proton spectra and the spectra of the clusters. The proton spectrum has the form $e^{-E/\tau}$ and the clusters exhibit the same energy distribution $e^{-E/\tau} \equiv (e^{-E/A\tau})^A$ where A is the mass of the cluster. Thus the shapes of the spectra of clusters of different mass are related by a power law when plotted against E/A, kinetic energy per nucleon. This relationship is found in the data[4,10,15] and supports the thermal aspects of the hot spot and the idea that its properties can be viewed directly by detecting particles that emerge without having to penetrate the target residue.

In central collisions, most of the hot spot decays into the surrounding target nucleus, heating it up and driving it apart. As the temperature changes and the target residue expands, fragments of different mass are emitted at different stages; one should therefore see several temperatures from the same type of event. This idea relates directly to an old question from high energy proton nucleus reactions[6] where many low energy ^{4}He particles were measured reflecting temperatures of 14-20 MeV but only few low energy ^{3}He particles were detected, whereas at higher fragment energies the ^{4}He were lower in cross section than the ^{3}He, the spectra of which indicated temperatures of up to 140 MeV. Figures 6 and 7 show ^{3}He and ^{4}He spectra from p + U and ^{20}Ne + U reactions. For a long time the ^{4}He emission at low ^{4}He energies was considered to come

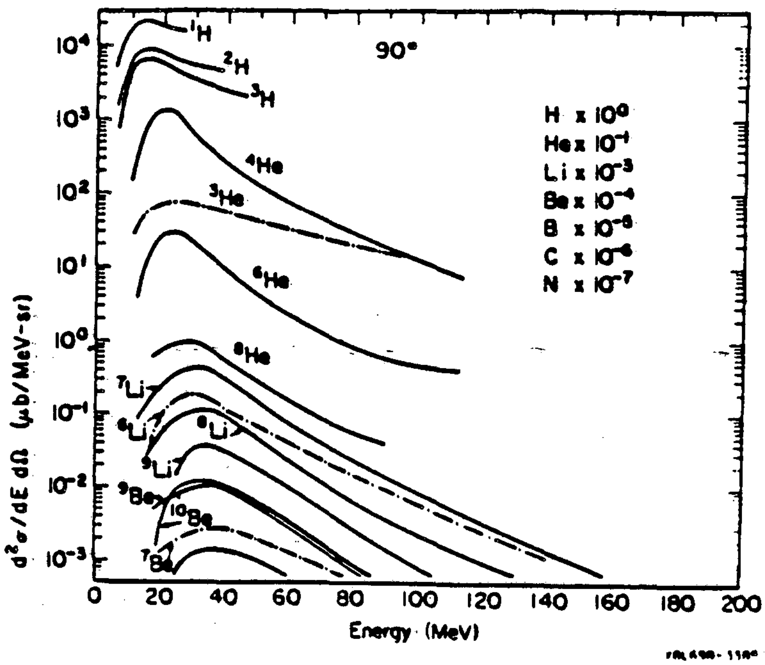

Fig. 6 Hydrogen and helium spectra from 5 GeV proton-U collisions.

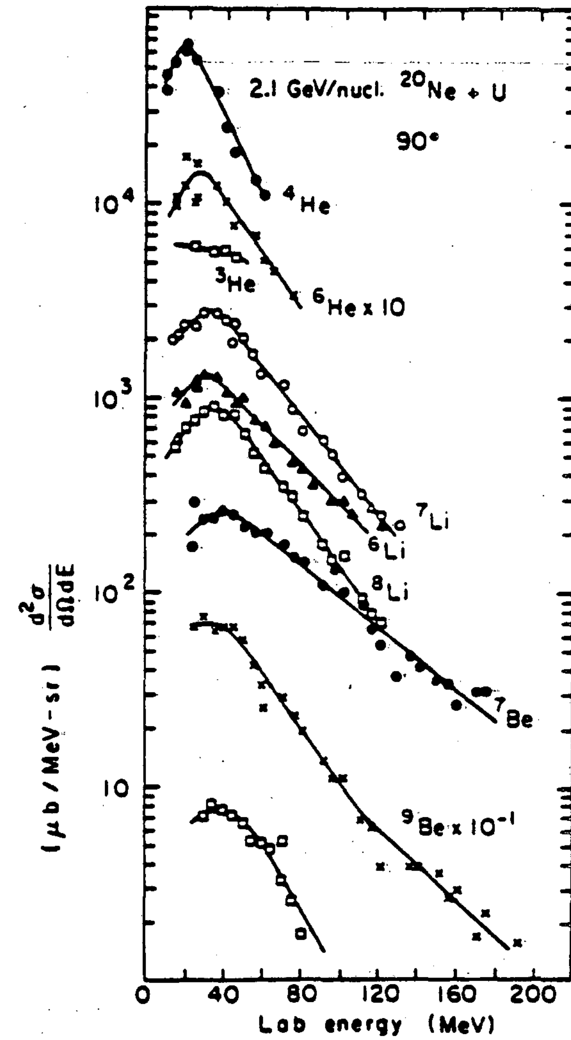

Fig. 7 Helium spectra from 42 GeV Ne on U.

from reactions with low deposition energies while the ^3He emission was to come from higher deposition energies.[6] It was found, however, that this is not true and that ^4He was also produced in the type of event characterized by a high associated charged particle multiplicity (see fig. 8). Thus, these ^3He and ^4He are emitted from the same kind of events where proton spectra tell of temperatures up to 150 MeV. One explanation for this ^3He-^4He puzzle is offered by the proposed hot spot picture: the hot spot emits p, d, t, and more ^3He than ^4He due to the very high temperature. The ^4He is emitted from colder parts of the target nucleus where its high binding energy favors its formation over that of ^3He. One can speculate even further on this process by imagining the whole target nucleus exploding and cooling down in the expansion phase. ^4He-condensation is favored if low temperatures are reached before the interaction stops. Then the ^4He emission is considered to come from a late stage of the reaction and the ^3He dominantly from an early stage.

5. Slow Fragments

The double differential cross sections at 90°, for fragment masses between 28 and 31 amu, are shown in Fig. 9 for all reactions studied. These spectra depict peaked distributions where the peak energy is usually associated with the Coulomb potential of the emitting system and the slope with its temperature.

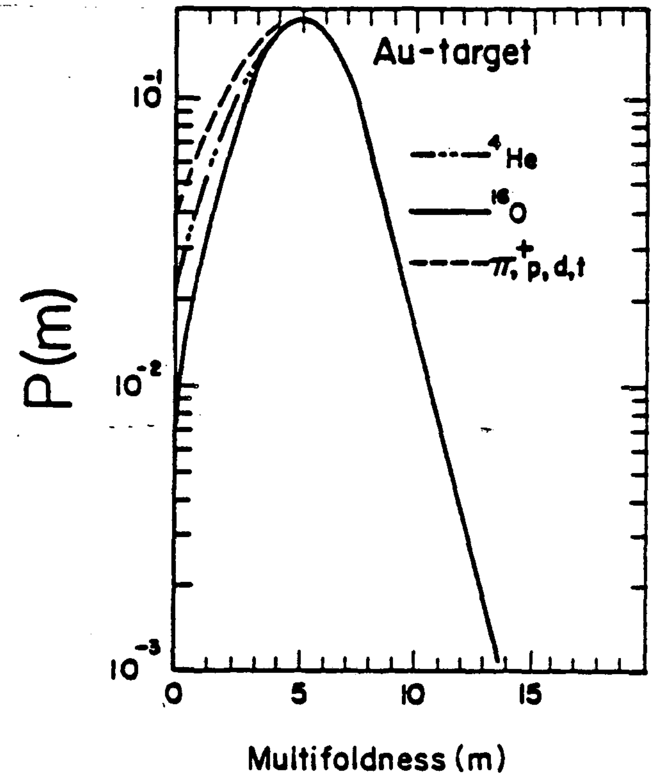

Fig. 8 Multifold coincidence distribution of charged particles associated with the detection of π^+, p, ^{16}O, and 20 MeV ^4He at 90° lab.

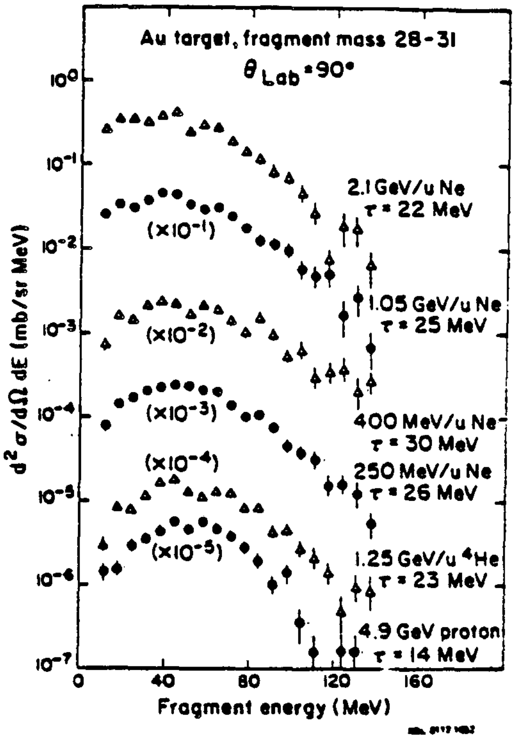

Fig. 9 Double differential cross section of mass 29-31 detected at 90°.

For all these various reactions there is astonishingly little change in shape. This is more evident when going to even heavier fragments in the mass range 120 to 140, i.e., 60 to 80 masses away from the target-nucleus (Fig. 10). Their spectra are nearly identical in shape and remind one of the slope of 8 MeV measured in projectile fragmentation at 0°[12]. From single particle inclusive measurements one cannot learn how the fragments from various mass regions are associated with each other, an essential question in the study of the reaction mechanism involved. For such an investigation these slow fragments with energies of around 0.5 to 5 MeV/u and masses from 6 to 40 amu are subject of the following discussion:

a) Are these fragments produced in an evaporation/fission-like process with acceleration due to the Coulomb field of a second body?
b) Are these fragments from a shattered target nucleus producing only a few large fragments?
c) Are these fragments condensation products from a nearly totally vaporized target nucleus?

In a recent experiment[8] with the system shown in fig. 1, it was clearly established that light fragments with masses from 10 to 30 were not produced via a fission-like process, leaving behind a large residue. Figure 11 shows the charged particle multiplicity associated with the detection of a fragment mass A. The majority of light mass fragments 20-40 have a different multiplicity from those of high masses, which otherwise could have been considered partner nuclei to the lighter masses in a fission-like decay. Thus the Coulomb peak in the light fragment spectra must refer to the Coulomb force from a many body system and explanation a) can be ruled out as the dominant process.

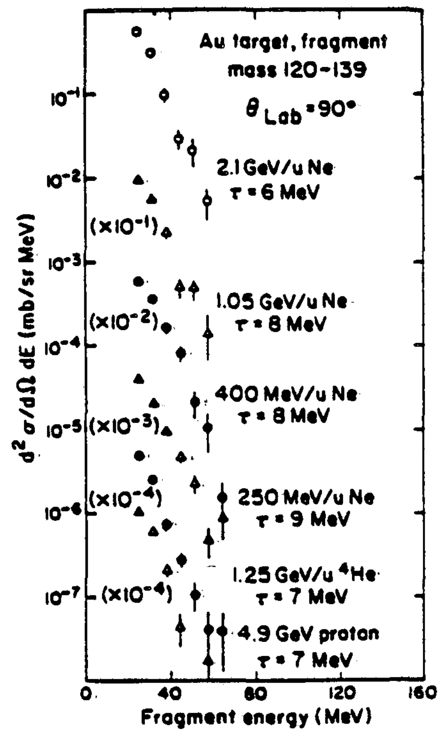

Fig. 10 Double differential cross section of mass 120–140 detected at 90°.

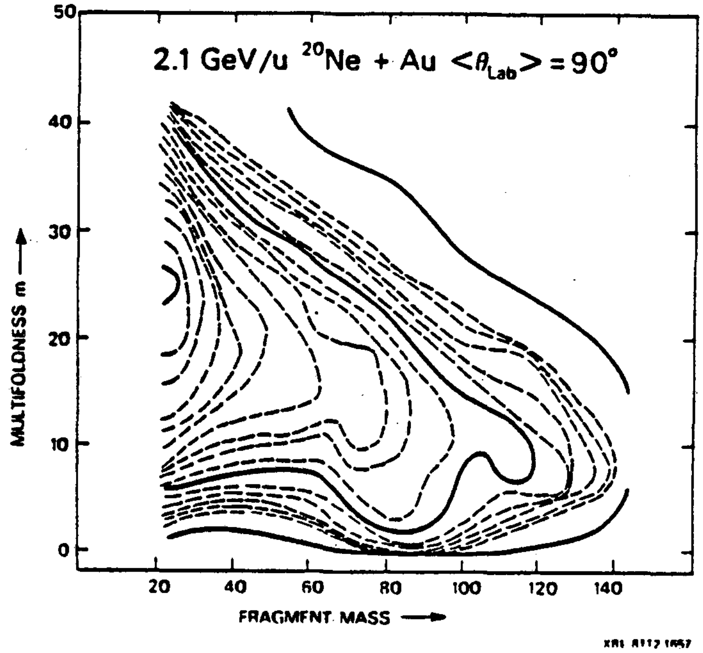

Fig. 11 Fast charged particle multifoldness as a function of the mass of the trigger particle.

The number of these light fragments produced in these reactions is shown in Fig. 12 (for the average event). The multiplicity of finding a given fragment mass in an event in which a trigger fragment of A = 20–40 is emitted at $\theta = 90^\circ$ is plotted for two different projectile energies. It is very low for associated fragments beyond a Z of 4, i.e., there are very few massive fragments, on the average, associated with a mass 20–40 fragment. Dominantly these fragments of A = 20–40 are associated with ^{4}He, Li particles. One can assume that there is also a large multiplicity of slow protons, deuterons, and tritons associated with these fragments.

For the bombarding energies between 250 MeV/u and 2.1 GeV/u one can state that the light fragment production is associated with a large multiplicity of fast charged particles, a substantial multiplicity of (H), He, Li fragments and only a very small multiplicity of heavy fragments. (At lower bombarding energies like 86 MeV/u this is not true any longer. There the disintegration of the target nucleus is much less violent and breakup into several large fragments has been observed as a substantial reaction channel[13].) Table I gives an account of the associated fragment masses when a trigger fragment with mass 20–40 is observed. The ratio of the ^{4}He cross section to that of slow protons below an energy of 25 MeV was extracted from earlier p-nucleus studies[6] and from neutron measurements[14] the number of neutrons was deduced to be approximately four times the number of protons. This yields roughly 24 neutrons and 6 protons at energies below 25 MeV. One observes that at 2.1 GeV/u the whole target mass has been accounted for, i.e., the incident Ne projectile caused the explosion of the Au nucleus and mechanism b) can thus be ruled out at high bombarding energies (2.1 GeV/u Ne).

At 8 GeV total incident energy it was found[7] that collisions leading to an emission of a slow fragment like carbon had the highest charged particle multiplicity, therefore coming from the most central collisions. Figure 13 shows that at total incident energies of 20 and 42 GeV, this is no longer true.

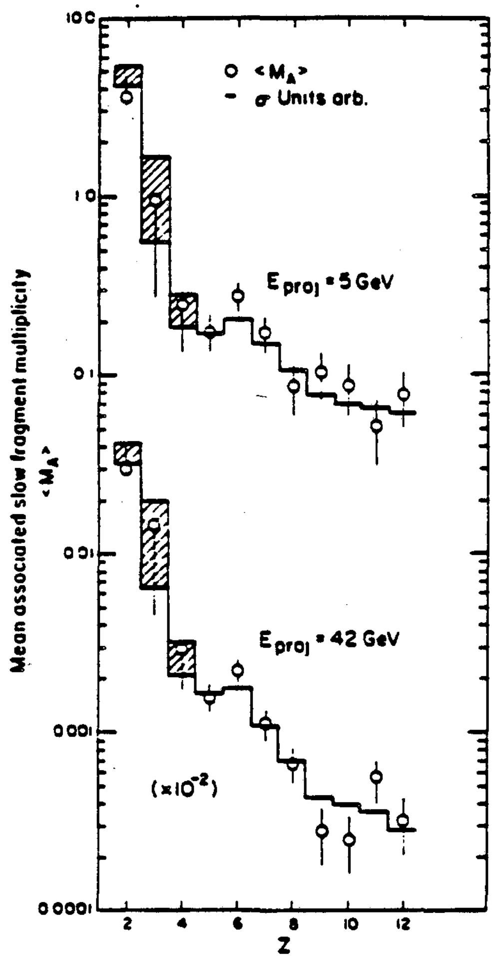

Fig. 12 Mean multiplicity of fragments with charge Z associated with a mass 20–40 fragment at ~90° for Ne + Au. Also fragment cross sections scaled arbitrarily for comparison of Z dependence.

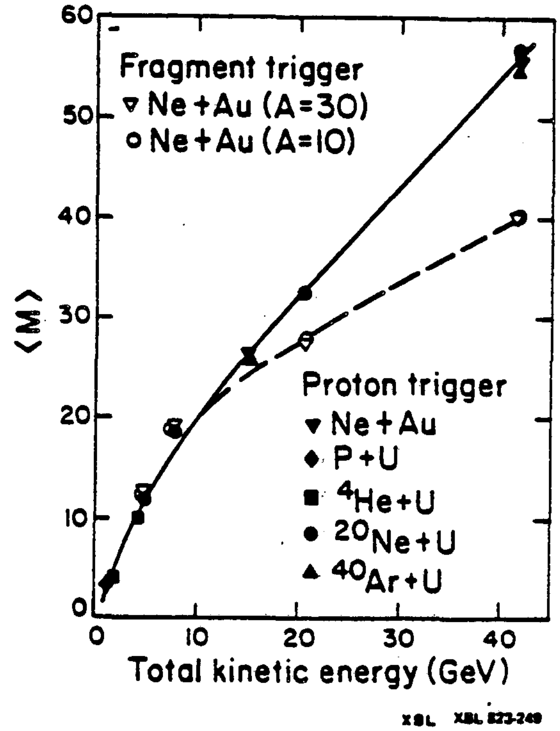

Fig. 13 Average charged particle multiplicity associated with proton emission and with slow light fragment emission into 90° as a function of total projectile energy.

TABLE I

MASS ACCOUNTING IN THE AVERAGE VIOLENT EVENT Ne + Au

Trigger Fragment: Mass 20 to 40	Beam Energy			
Associated Masses:	400 MeV/u		2100 MeV/u	
Slow fragments $\sum_{A=4}^{40} \langle M_{slow} \rangle A$	44		39	
Fast charged part. <M>	20	126	42	178
Fast neutrons	32		67	
Slow n (~24) and p (~6) below 25 MeV	~30		~30	

11 In these cases the slow fragment emission is associated with a 50% lower charged particle multiplicity than are protons emitted to 90°[4)] showing that at high energies there are more energetic explosions than the ones that lead to a mass 20-40 fragment emission.

6. Condensation

The reported data on ^3He-^4He productions, on the slow fragment emissions, their associated slow and fast charged particle multiplicities with their dependence on incident energy, all that has to be kept in mind when the total yield curve is compared for masses from 4 to ~30. In fig. 14 this mass yield curve is plotted for the systems investigated in this experiment. Note the difference in the cross section of 1.4b to 13b when extrapolated values from ref. 15) are compared with data covering the low-energy part of the spectrum inaccessible to the high-energy data. To describe these data simple fireball-yield curves[16)] have been plotted with the temperature as a search parameter (fig. 14). The steep fall off of the calculations after Z = 6 is not physical and mostly due to the fact that only nuclei up to oxygen are included in the various decay schemes feeding the lighter elements. It is found that the light particle yield dominated by high-energy particles is best described with a temperature of ~140 MeV, whereas the fragment yield of slow particles is best described by a temperature of ~18-20 MeV. These findings are in line with the temperatures extracted from the spectra. As it was pointed out earlier in this report, a temperature of 140 MeV cannot be reached in a fireball geometry without invoking a decrease of the volume and large collective effects, which turn more kinetic energy into heat than is possible in totally inelastic collisions. even of equal size objects. The temperature of 20 MeV obtained from the fit of the slow fragment yield curve points towards a large energy flux into the "spectator matter" so that the whole concept of spectator-participant zoning is no longer appropriate for these collisions.

In the limit of large number of constituents in a cluster one might ignore nuclear structure and look to a condensation model to calculate the average yield of the clusters. As the word evaporation is inappropriate for the emission of the ^4He in a reaction leading to total disintegration of the nucleus and since the heavier fragments (C,N,O) are from similar events as are the ^4He, it is inviting to assume the same production mechanism for both. Following the "theory of condensation and the critical point" by M.E. Fisher,[17)] one can write down the probability to find a cluster of size A condensed out of a vapour to be:

$$P_A \propto A^{-\tau} \text{ with } \tau \text{ typically 2.33.}$$

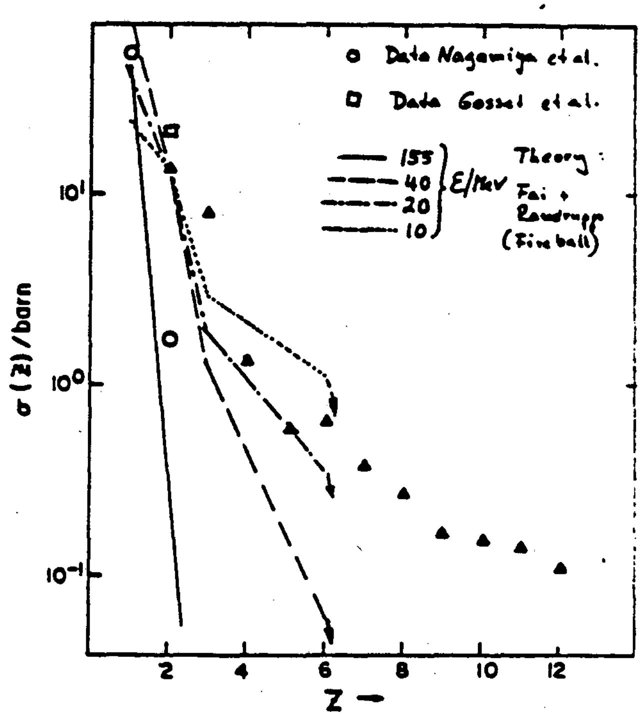

Fig. 14 Mass yield curves for element emission compared to fireball calculations. The yield curve labeled 140 MeV is a calculation yielding absolute cross sections. The curves labeled 10-20-40 MeV are arbitrarily normalized.

This formula is valid if A is large and the cluster is spherical. In Fig. 15 the cross sections for fragment emission are plotted and compared with such a prediction. It is astonishing how closely such a simple formula describes the data. especially since the finite size of phase space is totally ignored. It must be mentioned that the Purdue-Fermilab collaboration[18] has brought our attention to this power law, describing the fragment cross sections of high energy proton nucleus interactions. We consider this power law to be indicative of the liquid-vapor phase transition, as described by Fisher.[17] The best fit seems to be for $\tau \approx 2.6$. As Fisher points out, the condensation can only take place if the critical point is reached where the entropy in the vapor is balanced by the surface tension of the droplet to be formed. It is our understanding of the high-energy data that beyond 20 GeV incident total energy the nuclear vapor can be heated up to higher temperatures and produce so much entropy that the system does not cool enough to reach that condensation point. This is what we observe at high energies (2.1 GeV/u) when the character of the fragment trigger changes, selecting less central collisions. The most central collisions at this energy contain too much entropy for heavy fragment production.

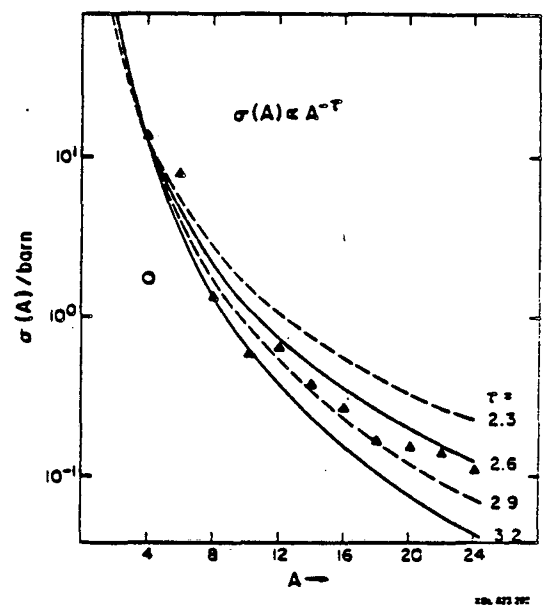

Fig. 15 Fragment yields compared to the power law $\sigma_A \propto A^{-\tau}$ (with varying from 2.33 to 3.2) of the general condensation model[16].

7. Conclusion

By means of an event characterization via the associated charged particle multiplicity it has been shown that several of the older model pictures, invented to understand single particle inclusive high-energy proton-nucleus data, are not adequate to describe correlation data. It was shown that the participant-spectator model needs revision and that a quick stopping in a small volume in the target nucleus is indicated. Furthermore, the whole nucleus is made to explode if the incident energy is high enough. The ^{4}He-^{3}He yields point towards an early and a late production of helium with a strong favoring of α-condensation at low temperatures[19] (fig. 16). The vapor-to-cluster condensation theory is astonishingly good at describing the observed mass yield.

This report is strongly based on the work of many collaborators[1,2,7,8,10]. We appreciate especially the support of A.M. Poskanzer, H.G. Ritter, and F. Weik

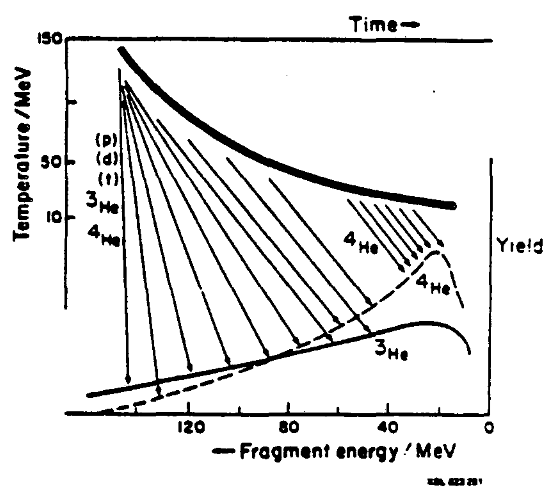

Fig. 16 Schematic view of the time dependent change of the temperature in the reaction, feeding at different times different parts of the He spectra.

13 from LBL and GSI and of S. Kaufman, E. Steinberg, and B. Wilkins from ANL. This work was supported in part by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

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