LBL-16135

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LBL--16135

DE83 014902

To be presented at the International Topical Meeting on "High Energy Nuclear Physics," Sixth International Balaton Topical Conference, Balatonfured, Hungary, June 6-11, 1983; and the Sixth High Energy Heavy Ion Study and Second Workshop on Anomalons, Lawrence Berkeley Laboratory, Berkeley, CA, June 28 - July 1, 1983

ASPECTS OF DATA ON THE BREAKUP OF HIGHLY EXCITED NUCLEI

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May 1983

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

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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.

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1. Introduction

There is an awakening of theoretical interest in the mechanisms by which nuclear fragments ($4 \leq A < 150$) are produced in violent collisions of heavy ions. With this in mind we review some aspects of the available experimental data and point out some challenging features against which to test the models.

The concept of evaporation is tremendously powerful when applied to pieces of nuclei of low excitation (1 or 2 MeV/u). Current interest focuses on higher excitations, at the point where the binding energy of the system vanishes. This is the transition from liquid nuclei to a gas of nucleons, and it may be that the critical phenomena that certainly exist in infinite nuclear matter will be manifest in finite nuclei under these conditions.

2. Favorable experimental conditions

One might study pieces of nuclear matter at excitation energies corresponding to the zero binding regime by making central nuclear collisions at bombarding energies around 50 MeV/u. However, in these lower energy collisions the multiplicity of fast charged particles is always small making it difficult to pick out central collisions. Furthermore, leading particles and the products of fast knock-out processes are not well separated in rapidity space from the fragments formed in the excited mid-rapidity zone. A clearer approach is to study asymmetric collisions at higher bombarding energies, measuring the products from the highly excited spectator residues. In such collisions the multiplicity of fast charged particles is an excellent parametrization of the violence of each collision and there is a clear rapidity separation between participants and spectators. Figure 1 shows angular distributions of a) heavy fragments from the target residue of a 42 GeV Ne + Au interaction and b) fast light particles from the fireball. The residue is almost stationary in the laboratory frame; the fireball has a large forward velocity. In the most violent collisions of Ne + Au at 2.1 GeV/u we have observed complete disintegration of the Au nucleus into fragments of $A \leq 10$, demonstrating sufficient transfer of energy to the spectator residues in such collisions to make them valuable probes of nuclear matter at zero binding energy.

3. Multifragmentation

For central collisions of asymmetric systems at high bombarding energy (Ne + Au above 250 MeV/u), we have observed[1] the disintegration of spectator residues into several large fragments. It seems likely that such a breakup process corresponds to an excitation energy too large to be appropriate to a conventional evaporation theory and calls for new models.

Figure 2 shows an example of such a measurement. Here a fragment of mass number $20 \leq A < 40$ from Ne + Au is the trigger for the event; these fragments emerge from the highest multiplicity collisions. We plot the multiplicity of coincident fragments as a function of their charge. Note that with 42 GeV Ne + Au one typically observes several neutrons and protons, three heliums, one lithium, one fragment with $4 \leq Z \leq 11$, and one fragment triggering the detectors for this measurement with Z of about 15.

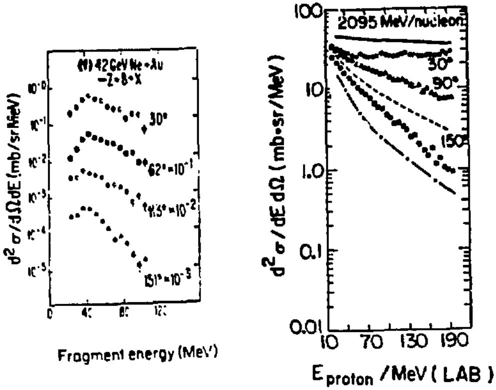

Figure 1. Angular distributions of light and heavy fragments from Ne induced reactions at 42 GeV.

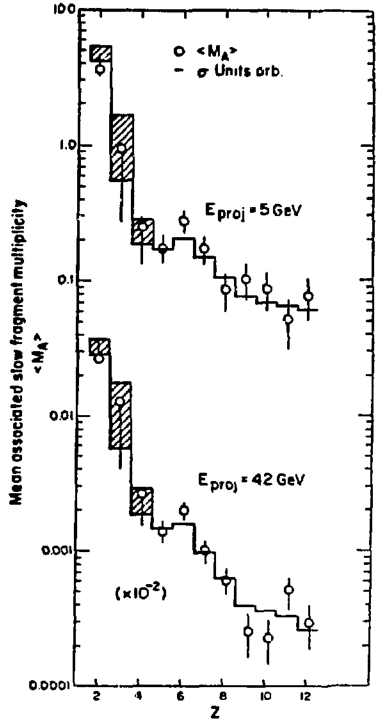

FIG. 2 Open circles show the mean multiplicities of fragments with charge Z associated with a trigger fragment of mass $A = 20-40$ detected at $\theta \simeq 90°$ from the reaction Ne + Au. The histogram represents the singles measurement of fragment yield as a function of fragment charge Z, scaled appropriately for comparison to the measured fragment multiplicities.

4. The mass-yield curve

a) It is important to realize that light and heavy fragments are produced from different classes of collision. In the case of Ne + Au at relativistic energies this can be demonstrated by observing the multiplicity of fast charged particles emitted from each collision.[1] High multiplicities are from large fireballs produced in central collisions and any spectator residues are born out of a violently disturbed system. Low multiplicities indicate peripheral collisions in which residues have low excitation. Figure 3 shows contours of yield against multiplicity of fast particles and the mass of fragments, from 42 GeV Ne + Au. There is a smooth trend; the highest multiplicity collisions produce the lightest fragments. Note the contribution of peripherally induced fission to the production of fragments around A = 90, accompanied by very few fast charged particles. This can be seen again[2] in fig. 4, which shows the fission yield peaked around 60 MeV, while the deep spallation contribution has a steeply falling spectrum at lower energies. So, for example, one should not attempt to invoke a single mechanism to explain the shape of the entire mass-yield curve.

b) At the low end of the mass yield curve an interesting fact shows up in the yield of the ^{3}He and ^{4}He.[3] The ^{3}He spectrum is very flat while the ^{4}He spectrum contains a very large cross section at low α-energies up to a total yield of 13 barns (fig. 5) with a slope parameter of 14-20 MeV. The conventional view is that alpha particles come from low energy deposition reactions while ^{3}He comes from high deposition energy collisions. We have found, however, that ^{3}He and ^{4}He have the same associated multiplicity of

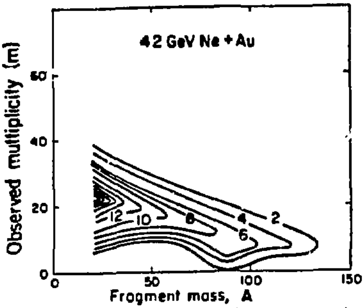

FIG. 3. Contours of fragment yield versus associated observed multiplicity and fragment mass for the reaction 42 GeV Ne + Au.

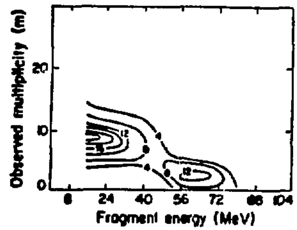

FIG. 4. Contours of fragment yield (arbitrary units) in the mass range $80 \leq A \leq 89$ at $\theta = 90°$ from the bombardment of ^{197}Au by ^{20}Ne projectiles at 250 MeV/u.

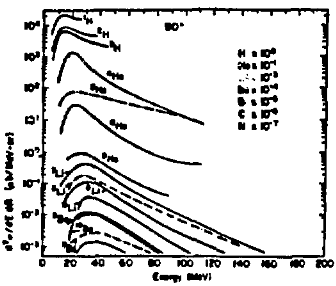

Fig. 5. Hydrogen and helium spectra from 5 GeV proton-U collisions.

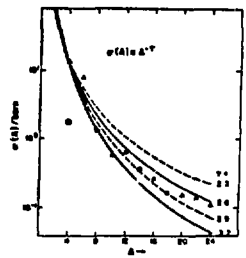

Fig. 5 Fragment yields compared to the power law $\sigma_A = A^{-\tau}$ (with τ varying from 2.33 to 3.2) of the general condensation model

fast charged particles,[4] suggesting that they are emitted from the same class of collisions. In this case the difference in their spectra can be explained by alpha particles emitted late in the lifetime of the cooling fireball, with a lower characteristic temperature.

c) The observed shape of the mass yield curve for A < 20 can be fit by a simple power law, $\sigma_{(A)} \propto A^{-2.6}$ (fig. 6), following suggestions of ref. 5 using the theory of condensation.[6] We considered this as a possible indication of a liquid-vapor phase transition. However, this same power law appears in the total energy spectrum of particles emitted by cosmic-ray sources.[7]

There one finds for the probability $\phi_p(E)$ to observe a particle of energy E

$$\phi_p(E) \sim (E + E_0)^{-2.6}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}\ \mathrm{MeV}^{-1} \qquad (E_0 = m\,c^2)$$

Rewritten as a function of mass A: $\phi_A(E) \sim (E + A\ 931)^{-2.6}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}\ \mathrm{MeV}^{-1}$.

In the frame moving with the mean particle velocity E is very small compared with E_0 ($E \ll A\ 931$). Thus: $\phi \sim (931 \times A)^{-2.6} \propto A^{-2.6}$.

In applying the condensation theory, temperatures of ~20 MeV have been discussed. In the cosmic-ray sources, however, these high temperatures are never considered. The coincidence in the power law observed in high energy nuclear reactions and in the particle spectrum of cosmic-ray sources might be fortuitous. On the other hand, it might indicate a common feature of nuclear fragmentation. Within the context of condensation it would point towards much hotter sources in the universe than previously considered.

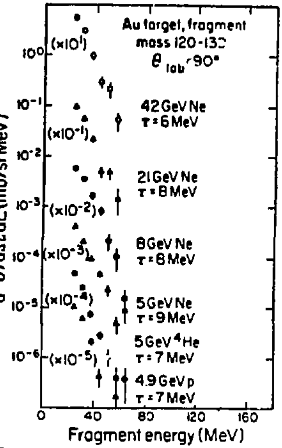

FIG. 7. Double differential cross sections for fragments falling into the heaviest mass bin, for each of the reactions studied. The exponential slope parameters (τ) are from a fit to the tails of the measured spectra.

d) The *fireball concept has been* extended to include composite particle production up to A = 20.[8,11] These calculations produce a mass yield curve of the correct shape in the range $1 \le A \le 11$ with an excitation of ≈20 MeV/u. Beyond mass 12 the model predicts yields less than experimentally observed.

The inability of fireball-chemical equilibrium models to describe the mass yield curve above A = 12 indicates departures from statistical mechanical equilibrium. It is of great interest to see a detailed comparison of this part of the mass yield curve to the predictions of condensation theory. Our data show that the production of fragments up to A = 30 at a given projectile energy are from the same class of violent collisions. Above A = 30 fragments are from more peripheral collisions.

e) In the upper part of the mass yield curve at 2/3 of the target mass fragments are observed to have spectra with a slope parameter of T_0 ~ 7–9 MeV independent of the projectile size or incident energy (fig. 7). We consider these fragments to be spectator residues from fairly clean-cut abrasion reactions with the spectra reflecting the momentum distribution the fragments had in the target nucleus.[9] However, a small perpendicular momentum transfer has been observed in projectile spectators in 4π data[10] and might also be part of the transverse momentum distribution of these heavy target fragments.

5. Fireball-residue coupling

Examination of the energy spectra of fragments from the residues of violent collisions shows little dependence of projectile mass and energy *(fig. 8), and the angular distributions show more or less forward peaking,* depending on projectile mass and energy (fig. 9). The size, velocity, and temperature of the fireball, however, varies enormously with projectile mass and energy.

One way to deal with this effect is to decouple the fireball from the residue breakup mechanism, simply allowing enough energy to cross into the residue to produce approximately the same excitation at all projectile energies. Linear momentum is also transferred to the residue to push it forward in accordance with the observed fragment angular distributions. Such a scenario might give rise to equilibrium behavior of the residue and statistical mechanics could then predict the breakup.[11] We find[1] that a residue excited to about 20 MeV/u, breaking up statistically, would approximately reproduce the measured energy spectra. The initial excitation energy is partly used up to break binding as the nuclear remnant breaks up into fragments, according to the statistical mechanical probability distribution. The remaining excitation is shared among the fragments as

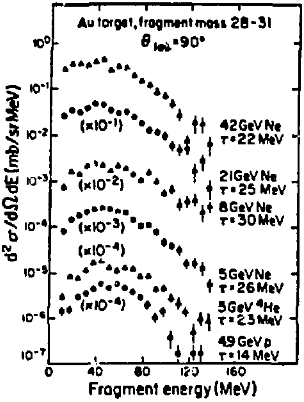

FIG. 8. Double differential cross sections for fragments falling into the lightest mass bin, for each of the reactions studied. The exponential slope parameters (τ) are from a fit to the tails of the spectra.

kinetic energy, and the resulting spectrum (when modified by the final stage Coulomb interaction) almost agrees with the data (fig. 10).

A totally different approach would be to couple the participants to the residue breakup mechanism directly.[12] For example, fast protons from the cascade or fireball could knock out preformed cold clusters of nucleons forming the observed fragments. Early results of such "cracking" phenomena look promising both in describing double differential cross sections and the observed mass yield curve. With regard to the earlier discussed observed power law in the particle spectra of cosmic-ray sources this model does not require high source temperatures.

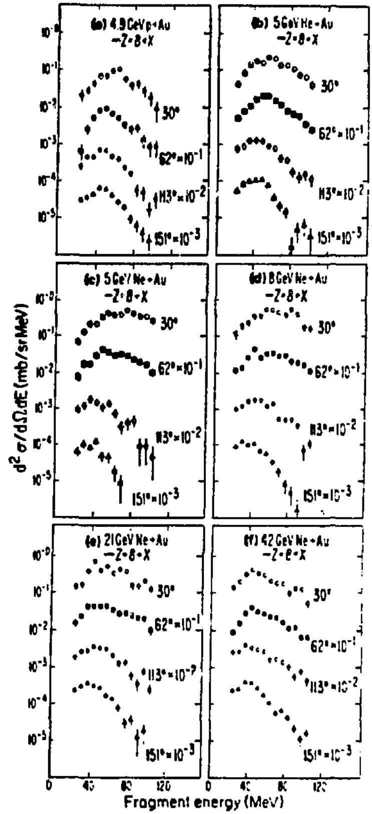

FIG. 9. Angular variation of the spectra of fragments of $Z = 8$ from the reactions (a) 4.9 GeV p + Au, (b) 5 GeV He + Au, (c) 5 GeV Ne + Au, (d) 8 GeV Ne + Au, (e) 21 GeV Ne + Au, and (f) 42 GeV Ne + Au.

6. Change of Mechanism

There are experimental results to show that fragments of a given mass (A = 30, say) originate in the most central collisions at low projectile energies while at higher projectile energies these same fragments are most likely to emerge from violent collisions. Figure 11 shows the multiplicity of fast charged particles for events in which "trigger" fragments or "trigger" protons were detected. The proton trigger comes from the fireball itself, and its detection necessarily weights the data towards the largest fireballs from the most violent collisions. Thus the trend of proton trigger multiplicities is that of the most violent (b = 0) collisions. The fragment trigger multiplicities follow this trend up to 10 GeV projectile energy, showing that these fragments emerge from the most violent collisions. At higher energies,

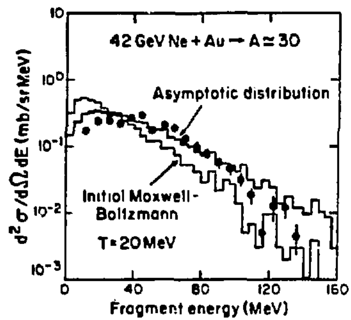

FIG. 10 Results of the Coulomb expansion calculation of the kinetic energy spectra of $A = 30$ fragments emerging from the Au target residue after a central collision induced by a 42 GeV Ne projectile.

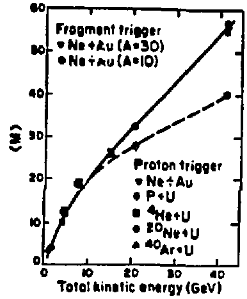

Fig. 11 Average charged particle multiplicity associated with proton emission and with slow light fragment emission into 90° as a function of total projectile energy.

however, the fragments emerge from collisions of less than maximum violence. The corollary is that at projectile energies above 10 GeV one can sometimes cause a Au nucleus to disintegrate completely into fragments of A < 10.

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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This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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