CENTRAL COLLISIONS OF RELATIVISTIC HEAVY IONS†

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Relativistic heavy ion collisions as they are now studied at Berkeley with the Bevalac are somewhat pragmatically subdivided into peripheral and central collisions. In a peripheral collision target and projectile nuclei interact only in the tails of their density distributions. Therefore only a small amount of energy and momentum is transferred and the multiplicities—as one can see in streamer chamber pictures—are small. In a more central collision, however, large amounts of nuclear matter interact and we have events with a very high multiplicity.

We have started an experimental program in an LBL-Marburg-GSI collaboration[1,2] to measure the emitted fragments electronically as to their mass, charge, energy, angle of emission, and associated multiplicity.

In this report I will first present our data of double differential cross sections which have been measured for high energy p, d, t, ^{3}He, and ^{4}He particles emitted from uranium targets irradiated with ^{20}Ne ions at 250, 400, and 2100 MeV/nucleon and ^{4}He ions at 400 MeV/nucleon. Then in the analysis, by using the shape and yield of the proton energy spectra, the shape and yield of the d, t, ^{3}He, and ^{4}He energy spectra can be deduced at all measured angles for all incident projectile energies assuming that they are formed by coalescence of cascade nucleons using a model analogous to that of Butler and Pearson, and Schwarzschild and Zupančič. Finally and most important, we find that the overall features of the proton inclusive spectra are fit without any adjustable parameter by a proposed nuclear fireball model. In this model the nucleons which are mutually swept out from the target and projectile form a hot quasi-equilibrated fireball which decays as an ideal gas.

Experimentally, we have measured the energy spectra from 30 to 120 MeV/nucleon at several laboratory angles for protons, deuterons, tritons, ^{3}He, and ^{4}He emitted from uranium bombarded with beams from the Bevalac. The hydrogen and helium isotopes were identified as to their charge and mass in a ΔE-E telescope consisting of a 2-mm thick silicon ΔE counter (300 mm^{2}) and a 10-cm long plastic scintillator as an E detector. For measuring the associated multiplicity of the emitted fragments we installed 16 plastic scintillators (tag counters) connected to 2 in. diameter photomultipliers around our scattering chamber. A special thin Al cover was built to serve as an absorber for protons up to 45 MeV and pions up to 20 MeV so that the tag counters do not measure the target evaporation products. Furthermore, the tag counters did not subtend the angle from 0° to 15° in order to avoid any events due to breakup of the projectile in a peripheral collision. A particle detected in the telescope opened for 40 nsec a gate in the 16 fold discriminator and coincidence latch of the 16 tag counters. Therefore a particle detected in the telescope was identified for A, Z, E, θ, and the relative multiplicity of the star it belonged to as well as for the information of which tag counters had fired. Thus a rough spatial distribution of the multiplicity events could be detected. Figure 1 shows the experimental layout.

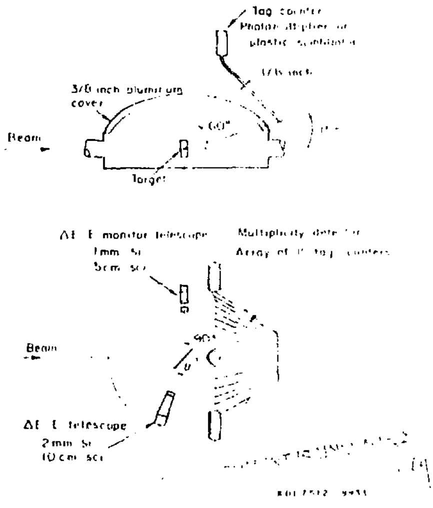

Figure 1. Scattering chamber with telescopes and multiplicity detector.

The relative cross sections, which are accurate to within 20%, were obtained by normalizing to a monitor telescope fixed at 90° with respect to the beam. The absolute cross sections were obtained by normalizing to previously measured data.[3] Double differential cross sections for the various emitted particles are presented in Fig. 2. Although many more angles have been measured, only some of the spectra are shown. The energy spectra

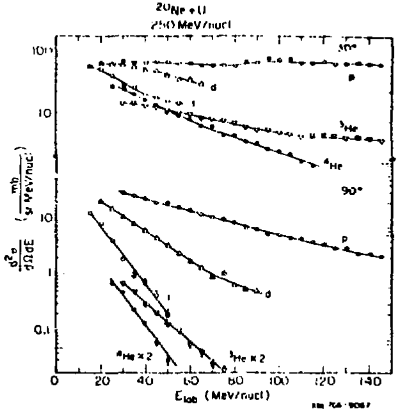

Figure 2. Double differential cross sections for p, d, t, ^3He, and ^4He emitted from $^{20}Ne + U$ at 250 MeV/nucleon.

of all products are smooth and show no peaks. The slopes of the energy spectra become steeper with increasing angle and also with increasing mass of the emitted particle.

The measured associated multiplicities are quite high. In Fig. 3 we see this multiplicity increase as we increase the projectile mass or as we increase the projectile energy. Remember that this multiplicity includes only the high energy part (fragments above ≈45 MeV/amu and pions above 20 MeV) of the star event. In order to obtain the absolute multiplicity one has to know the full spatial distribution of the tag-particles and one has to correct for statistical effects in the measurements.

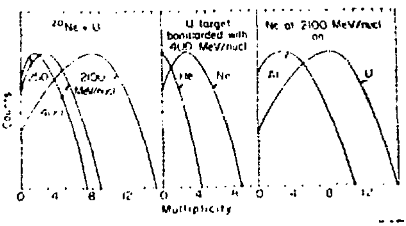

Figure 3. Multiplicity distribution in the 15 tag counters if a ^3He has been detected in the telescope at 60° lab.

The analysis of these data was first focused on the question of whether the complex fragments were related to each other.

In high energy proton induced reactions the observation of deuterons was explained by Butler and Pearson[4] as the coalescence of cascade nucleons. In this model, which was modified by Schwarzschild and Zupančič,[5] the deuteron density in momentum space is predicted to be proportional to the proton density times the probability of finding a neutron within a small sphere of radius p_0 around the proton momentum. P. J. Johansen in our group has extended this formalism to more complex particles in the limit of low density in momentum space and high multiplicity.[1]

We apply this formalism to our heavy ion data assuming that the protons and neutrons have the same momentum distribution and that their yield is equal to the neutron to proton ratio in the projectile plus target. Thus we allow only for one free parameter p_0 and use the measured proton spectra as representatives for the nucleon distributions.

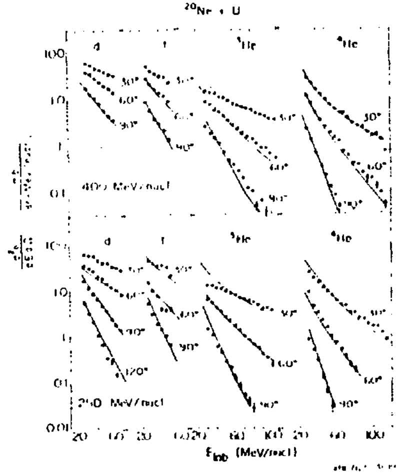

Figure 4. Comparison of experimental double differential cross sections (dots) with calculations of the coalescence model.

In Fig. 4 we show measured double differential cross-sections for d, t, ^3He, ^4He compared to calculations of such a coalescence process. For each projectile incident energy and fragment we extracted one value for p_0 which are all around 110 140 MeV/c. The p_0 values are remarkably uniform even though absorbed into this parameter are the many factors like nuclear structure of the fragments, correlations, etc., not explicitly accounted for in this simple model.

Now that we have a link between the emitted complex fragments and the emitted protons, we have to concentrate on the understanding of the mechanism which leads to the emission of nucleons with a smooth energy distribution and in a forward peaked angular distribution.

A very simple model[7] is proposed here consisting of a fireball, formed from the nucleons mutually swept out from the target and projectile, which decays as an ideal gas. The model uses the geometrical concepts of the abrasion model,[?] the free expansion of an ideal gas, and for the extension to higher energies, the statistical thermodynamics of strong interactions by Hagedorn.[?] The geometrical concepts of this model are illustrated in Fig. 5. It is assumed that the target and projectile are spheres with radius equal to 1.2 $A^{1/3}$, and that the projectile and target make clean cylindrical cuts through each other,[6] leaving a spectator piece of the target and, if the impact parameter is large enough, also a spectator piece of the projectile. We calculate as a function of

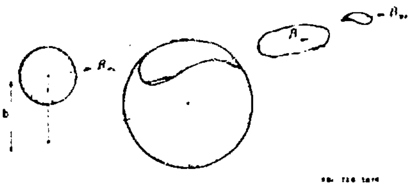

Figure 5. Artist's view of the exploding fireball which moved on with the velocity which the spectators ... of the projectile ... with b_{imp} ... cap and target spectator ... particles emitted in their direction from the exploding fireball ... shown.

impact parameter b the number of nucleons swept out from the projectile and target and from kinematics the laboratory velocity of their center of mass. In the center of mass of these nucleons the available energy per nucleon—which is assumed to be their kinetic energy minus 8 MeV binding energy—is transformed into "heat" leading to a quasi-equilibrated nuclear "fireball". The fireball is treated relativistically as an ideal gas with temperature determined by the available energy per nucleon. The data are compared to this model without any adjustable parameters in Fig. 6 and good agreement is obtained for 250 and 400 MeV/nucleon incident ^{20}Ne and 400 MeV/nucleon ^{4}He. On the average the fireball contains 64 nucleons and is at a temperature of 50 MeV (for 400 MeV/nucleon ^{20}Ne).

At 2.1 GeV/nucleon the calculation fails to describe the data as shown by the solid lines in Fig. 6 because it predicts

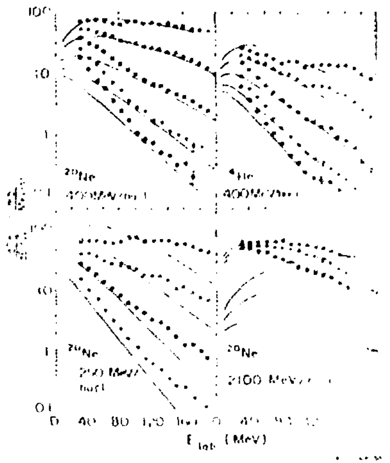

Figure 6. ... the 2.1 GeV/nucleon ... data, two fireballs with only ... of their original relative longitudinal momentum ... of ... dissipated into heat ... measured distributions.

values of temperature and [illegible] ity which are too large even when we have included a cooling effect by allowing an internal excitation of the nucleons to baryon resonances. One way to [illegible] the shape of the data [illegible] curve) [illegible] and target fireballs [illegible] their original relative longitudinal momentum in their center of [illegible] domized and dissipated into heat [illegible] to the same temperature.

This simple model [illegible] first attempt quantitatively [illegible] [illegible] the measured proton [illegible] spectra [illegible] qualitatively [illegible] shadow effect caused by the [illegible] pieces of the target and the projectile which we have observed in the [illegible] pattern as a function of the [illegible] distribution of the particle [illegible] the [illegible]. The present [illegible] enables us to predict [illegible] tics and with some modification [illegible] inclusive spectra and multi[illegible]

It will be interesting to see "microscopic justification" for the [illegible] temperature and the success of this model or to find out how well other models, like cascade calculation, can describe all these data.

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