TRANSVERSE ENERGY PRODUCTION AND THE EQUATION OF STATE OF NUCLEAR MATTER

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Abstract

In nuclear collisions of Au+Au, Nb+Nb and Ca+Ca at bombarding energies between 150 and 800 MeV per nucleon transverse energy and transverse momenta of light particles are studied event by event at $\theta = 90°$ in the center of mass system. At all energies a rise of the mean transverse energy per nucleon is observed with increasing charged particle multiplicity. Particularly large values of $E_\perp$ have been found for ^3He - fragments. The hydrodynamical picture is discussed for a possible separation of the collective flow and the thermal parts of the $E_\perp$ - spectrum. From this, evidence for a rather stiff equation of state is found. Transverse particle energies, measured in the target rapidity region of 60 and 200 AGeV oxygen and sulphur induced reactions, indicate a surprisingly high energy transfer to the target spectator.

1. Introduction

The possibility to investigate nuclear matter at high density and excitation energy and to derive an equation of state for this form of matter is one of the major motivations for performing relativistic heavy ion experiments.

Recently, collective sidewards flow of nuclear matter has been established [1] and interpreted as a signature of compressional effects, as predicted by the hydrodynamical model [2,3]. The amount of energy contained in the *directed* collective motion was estimated to be 10-20 % of the total available kinetic energy in the center of mass (c.m.) system. Furthermore, an increasing cluster production was observed with increasing multiplicities of charged particles, indicating that particles are more correlated in phase space the more central the collision, pointing towards another collective phenomena [4]. Previous investigations of spectra at 90° in the c.m.-system in Ca+Ca and Nb+Nb collisions [5] have given support to the picture of a blast-wave containing an ordered radial expansion- and an uncorrelated thermal part [6]. This superposition of different contributions to the transverse energy spectra makes the extraction of temperatures via ad hoc Boltzmann parameterizations of the measured proton spectra very problematic and the inverse slope-parameters extracted by this method can represent only an *upper limit* for the temperature [6]. This has again been confirmed by a recent analysis, where the thermal energy of a colliding system was cal-

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culated from the observed pion yields [7]. The temperatures, as calculated by this thermodynamical model which includes also the compressional energy, are significantly lower than those extracted from the spectra via Boltzmann fits. The goal of this study is to investigate in detail the transverse energy, $E_{\perp}$, carried out by the various light fragments, p, d, t, ^{3}He and ^{4}He and to derive information about the equation of state (EOS) of nuclear matter from the discrepancy between the measured and calculated thermal mean transverse energies.

2. Results

2.1 Symmetric systems at bombarding energies of 150-800 AMeV

Collisions of Au+Au, Nb+Nb and Ca+Ca at several beam energies between 150 and 800 MeV per nucleon have been measured with the Plastic Ball detector-system [8] at the Bevalac in a minimum bias trigger mode. In the Plastic Ball charged reaction products up to ^{4}He are well identified. Their high multiplicity measured over the full 4π solid angle of the detector system allows one to evaluate mean values of the transverse energies and momenta of protons and light composites with sufficient statistical significance in each single event and to directly relate these values to other event specific observables like particle multiplicities (i.e. impact parameters) or flow angles, for example.

In fig. 1 contour lines of the event yield accumulated in the minimum bias trigger are shown in the $< E_{\perp}/particle >_{event}$ versus participant proton multiplicity (N_p) plane for the reaction Au+Au at 250 MeV per nucleon. N_p is defined to include also the protons bound in clusters up to ^{4}He, but to exclude particles in the projectile and target spectator regions [4]. Apart from the very low multiplicity events ($N_p < 10$ in fig. 1), a narrow distribution of the means analyzed event by event and a strong rise with increasing multiplicity is observed, demonstrating a strong correlation between the centrality of the event and the mean transverse energy per particle. Since the main interest is in the properties of participant matter, the following analysis has been restricted to particles observed at $\theta_{cm}= 90°$ where spectator contributions are minimal for kinematical reasons. A systematic study of the bombarding energy dependence of the mean transverse proton energy is shown in fig. 2 for Au+Au collisions at E_{lab} = 150, 250, 400, 650 and 800 MeV per nucleon. Since the average multiplicity depends on the bombarding energy and the projectile-target mass, the events have now been classified according to the normalized participant proton multiplicity, N_p/N_p^{max} [9], which allows a meaningful comparison of the different systems. At all energies a significant increase of the mean transverse proton energy with multiplicity is observed. The maximum values, attained in most central collisions, rise from $E \cong 70$ MeV at 150 MeV per nucleon up to $\cong$ 160 MeV at 800 MeV per nucleon incident energy. Systematic errors increase

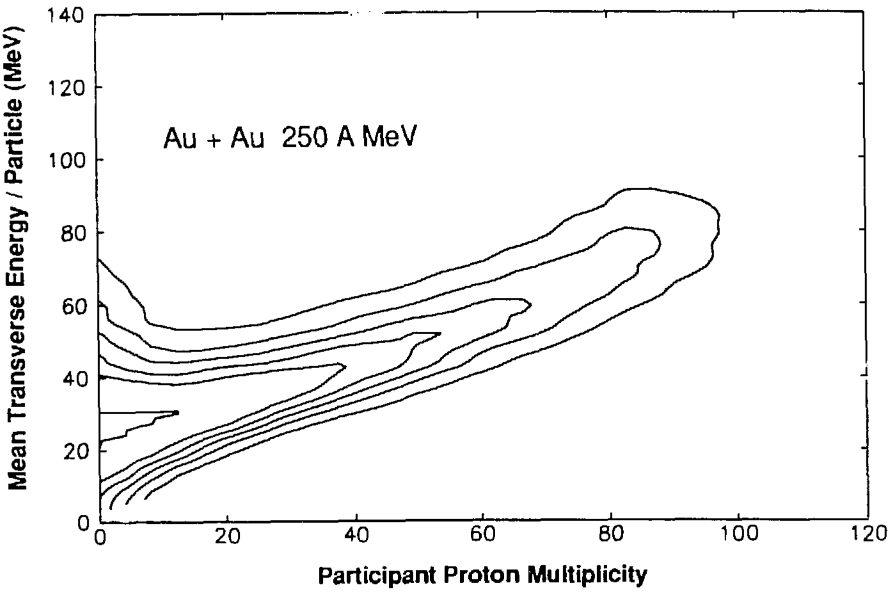

Figure 1: Contour plot (linear contours) of the mean transverse energy per particle ($<Et/particle>_{event}$) vs participant proton multiplicity (N_p) for Au+Au collisions at 250 MeV per nucleon.

with bombarding energy from <7 % up to ≈15 % at the highest energies.

It has been suggested in a previous paper [5] that the increase of the apparent temperature, i.e. the mean transverse energy per particle, with multiplicity may be caused partly by the increasing formation of composite particles which reduces the number of particles and therefore the number of degrees of freedom, thus raising the energy per particle. Let us study therefore the transverse energy of protons and composites individually. Since the formation of bound nuclei reduces only the number of *particles*, but not the number of *nucleons* emerging from the hot system, the mean kinetic energy per nucleon, $< E_{\perp}/nucleon >_{event}$ should - in a simple coalescence or fireball picture - stay constant as a function of multiplicity. Some representative results of such an analysis are shown in fig. 3 for Au+Au and Nb+Nb collisions at 250 MeV per nucleon incident energy. Here the mean transverse energies of p, d, t, ^{3}He and ^{4}He (upper half of the figure) are compared to their transverse energies per nucleon (lower part of the figure). Also, the average transverse energy per nucleon calculated from the sum of protons and the light composites is shown in the lower part of the figure. The Au+Au system still shows a significant increase of $< E_{\perp}/nucleon >_{event}$ of about 20 % when taking into account all particles up to ^{4}He. Only a weak dependence is found for Nb+Nb collisions. This difference might be explained, both, by the lower composite particle to proton ratios and by the weaker increase of the latter ones as a

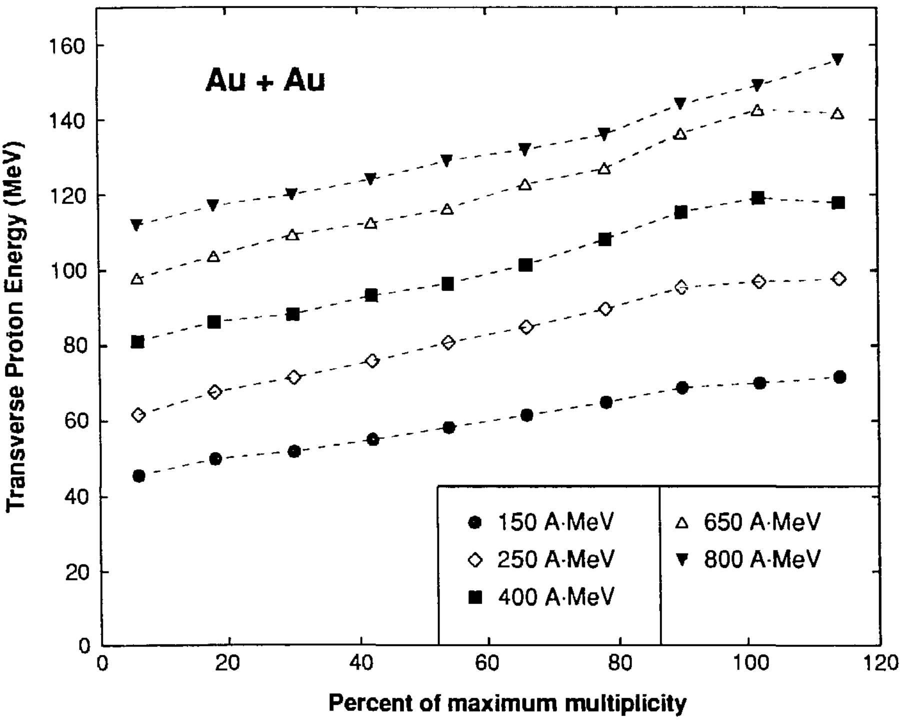

Figure 2: Mean transverse proton energy at θ_{cm} = 90° as a function of the normalized participant proton multiplicity (N_p/N_p^{max}) for Au+Au collisions at different beam energies between 150 and 800 MeV per nucleon. (The statistical errors are of the order of the size of the drawn symbols. Systematic errors increase with bombarding energy from <7 % up to 15 % at the highest energies.)

function of multiplicity in the Nb+Nb system [10]. It should be mentioned that in this calculation of $< E_\perp/nucleon >$ the free neutrons, that cannot be detected in the Plastic Ball, have been ignored. If the mean transverse energy of neutrons as a function of multiplicity would be assumed to be comparable to that of protons, then this contribution to the sum would result in a slight increase in the curve of Nb+Nb as well.

Inspecting now the transverse energies of the different particles themselves (upper part of fig. 3), we observe no significant differences in $< E_\perp/particle >$ between hydrogen isotopes (p, d, t) as one would expect from a pure fireball picture when the different particle species are in thermal equilibrium. However, ^{4}He and in particular ^{3}He - fragments exhibit a strong deviation to higher values. It should be pointed out that the selected θ_{cm}= 90° spectra are, due to the c.m.-boost, not affected by the particle dependent low-energy cutoffs in the detector, so that detector biases can be ruled out to cause this effect. Systematic errors, however, may be introduced by the limited particle identification of ^{3}He and ^{4}He in the Plastic Ball (see. ref. [8]). This effect could result in an uncertainty in the transverse energy of about 10-15 %

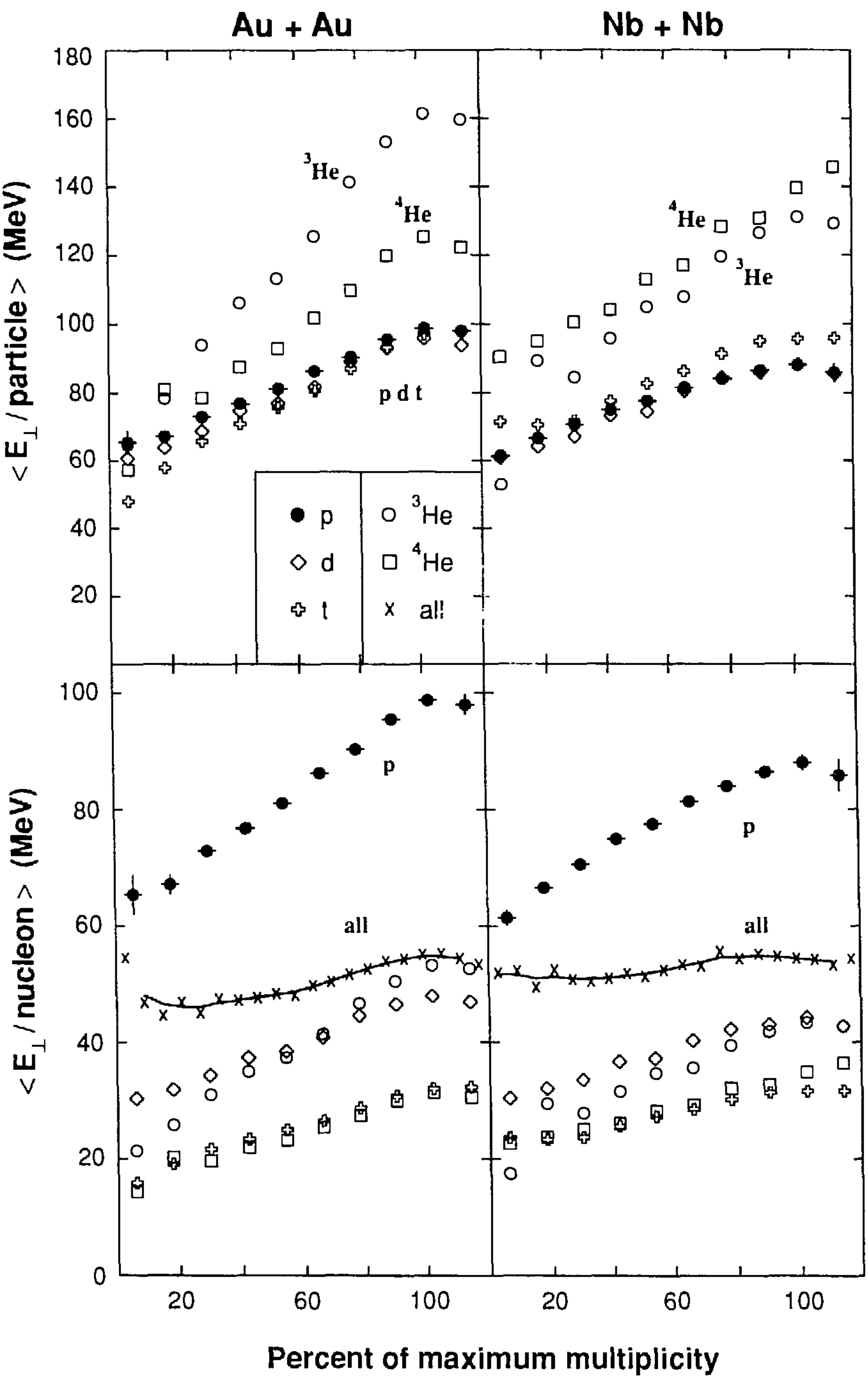

Figure 3: *Mean transverse energy per particle (upper half) and per nucleon (lower half) of p,d,t,^{3}He and ^{4}He at θ_{cm} = 90° as a function of normalized multiplicity and the mean transverse energy per nucleon for the whole set of particles for collisions of Au+Au and Nb+Nb at 250 MeV per nucleon, respectively. (For errors see fig. caption 2)*

when the yields of ^{3}He and ^{4}He are very different. A possible explanation for this "^{3}He-puzzle", also observed in asymmetric heavy-ion collisions, was proposed in ref. [11]. It was argued that ^{3}He may predominantly be emitted from the hot parts of the nucleus, thus being created in an early stage of the reaction, whereas the emission of ^{4}He and heavier particles was considered to come from a later stage. In addition, neutron rich systems, like Au+Au, are affected by the "proton robbing" of the light cluster production, i.e. the emission of p, d, ^{3}He and ^{4}He increases the *N/Z* -ratio in the remaining residue of the emitting system, thus reducing the yield of neutron poor isotopes with low kinetic energies. The latter seems to be confirmed by the observation that the strikingly high transverse energy of ^{3}He drops by more than 20 % when going from Au+Au to Nb+Nb collisions. The ^{4}He and proton spectra on the other hand do not show any significant projectile-target dependence. Coulomb repulsion, which could be considered a possible source of the increased transverse energies of the Helium isotopes, seems therefore to be of minor importance only. The situation is somewhat different for Ca+Ca, which is the lightest system investigated here. The transverse energies, attained in central collisions of the two heavier systems cannot be reached for any of the fragments, as may be due to insufficient stopping and transparency effects. This finding would be interesting to compare with recent model calculations of ref. [12] where momentum dependent interactions are reducing the effective number of nucleon-nucleon collisions in the reaction. In the following analysis only data of the more massive Au+Au and Nb+Nb systems have therefore been used. As discussed above, the mean transverse energy per particle cannot be related directly to the temperature, because of the different contributions to the energy spectra. However, if we ignore for the following discussion the ^{3}He puzzle and concentrate on the fact that the mean transverse energy per particle is the same for all hydrogen isotopes, i.e. for the major part of the cross section, and make the assumption that nearly all of the available c.m.-energy resides exclusively in thermal and compressional energy at the moment of highest density then

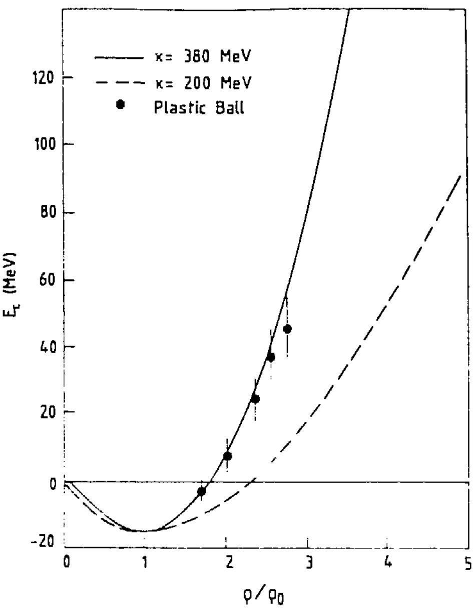

Figure 4: Equation of state from the present date compared to Skyrme equations of state with κ=200 MeV and κ=380 MeV as used in the VUU theory [14].

one may interpret the observed transverse energy as being the sum of

$$E_{\perp} = E_{therm} + E_{compr} + E_{coul}$$

where E_{therm} is the thermal excitation energy and $E_{compr} + E_{coul}$ is the potential energy associated with the initial compression and the repulsive Coulomb forces. For the reasons discussed above, the latter is assumed to be negligible. Using this formula and a reliable model providing us with the thermal energy as a function of bombarding energy, one may calculate the ratio between thermal and compression energy to derive information on the EOS of nuclear matter. The model that has been used for this purpose is that of Hahn and Stöcker [7] which has been able to reproduce measured pion multiplicities over about eight orders in magnitude in the bombarding energy range from 30 MeV per nucleon up to 4 GeV per nucleon. The temperature, i.e. the thermal energy, predicted by that model, and the sum of the compressional and thermal energy taken from the present set of data, are listed in Table 1 for all bombarding energies studied here. With these model dependent assumptions we then interpret ≈ 40 % of the total kinetic c.m. energy being converted into compressional energy in the moment of highest density. The resulting equation of state is plotted in fig. 4 as a function of the density achieved in the shock zone, as obtained in the same way from solving the Rankine-Hugoniot shock compression equations as done in the model of ref. [7]. The data-points are fairly in line with the stiff EOS plotted as a solid line in this figure, which is the same EOS as used in recent VUU-calculations that were able to describe the transverse energy flow [13,14] and the pion yield.

Table1: Transverse energies of protons at $\theta_{cm} = 90°$ and temperatures, calculated from ref. [7], at different beam energies.

E_{lab} (MeV)	$E_{\perp}^{data}$ (MeV)	T^{π} (MeV)
150	70	27
250	97	37
400	119	46
650	142	62
800	157	69

2.2 Asymmetric systems at bombarding energies of 60 and 200 AGeV

In the second part of this talk we will present some preliminary results on oxygen and sulphur induced reactions at 60 and 200 AGeV, measured with the Plastic Ball detector in the WA80 setup [16] at the CERN SPS. Because of the strongly forward focussed particle emission pattern in ultrarelativistic heavy-ion collisions and also due to the limited geometrical acceptance of the Plastic Ball ($30° \leq \theta_{lab} \leq 160°$), fragments were only measured in the

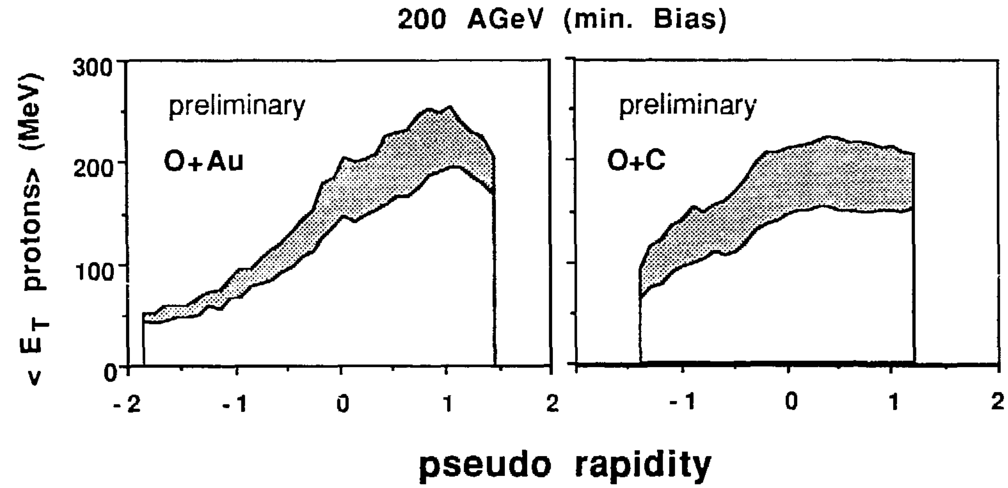

Figure 5: *Mean transverse proton energy as a function of pseudorapidity for 200 AGeV O+Au and O+C collisions. Shadowed area indicates the systematic error.*

target rapidity for this type of reactions. The analysis may therefore be regarded as an extension of the detailed studies of "participant" matter at relativistic energies to the study of "spectator" matter formed at ultrarelativistic heavy-ion collsions. Since neither the effective center of mass of the asymmetric systems nor the rest frame of the target spectator are known a priory, particle spectra were investigated in the laboratory system only. Figure 5 shows as an representative example the mean transverse proton energies from 200 AGeV minimum bias O+Au and O+C reactions as a function of the pseudorapidity, η, ($\eta = -\ln \tan(\theta_{lab}/2)$). The shadowed areas indicate the systematic error of these measurements which is mainly due to inability to separate very high energetic protons from punch through pions. For both systems, there is an indication of a maximum of about 200 MeV. Assuming that this structure is due to underlying physics, i.e. due to the target spectator source and not only caused by detector limitations, a longitudinal momentum transfer to the target residue of ≈ 500 MeV/c per nucleon can be estimated. Figure 6 shows the mean transverse proton energy, measured in the target rapidity region of 200 AGeV O+Au reactions, as a function of the centrality of the event, defined by the energy loss of the projectile [16]. For comparison, transverse proton energies measured in the central rapidity region of 800 AMeV Au+Au collisions are included. Evidently, there is a surprisingly high energy transfer to the target spectator which makes its excitation energy comparable to that of a fireball created at top Bevalac energies. Similar conclusions have also been drawn from the observed high entropy production [17]. Counting the number of baryons emitted into the target rapidity reveals furthermore a complete desintegration of the target matter into light fragments in very central collisions.

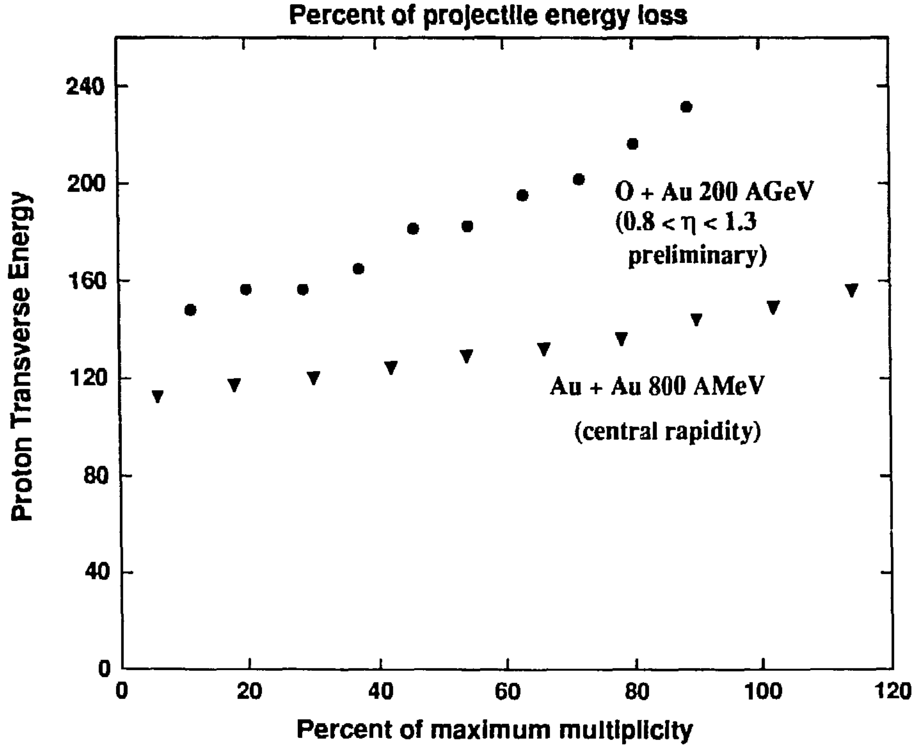

Figure 6: *Mean transverse proton energy as a function of the centrality of the event for 200 AGeV O+Au reactions in the target rapidity region and for 800 AMeV Au+Au reactions at central rapidities.*

Comparing different systems at 60 and 200 AGeV, we find only a very weak dependence of the transverse proton energies on the bombarding energy and a general trend of increasing values with increasing projectile and target mass.

3. Conclusion

We have presented data on transverse particle energies as a function of multiplicity and projectile-target mass at bombarding energies ranging from 150 MeV per nucleon up to 200 GeV per nucleon. For each particle type a strong increase in $E_\perp$ */ particle* as a function of multiplicity has been observed. At Bevalac energies this effect is strongest for helium isotopes. The hydrogen isotopes seem to be in thermal equilibrium since they show the same mean transverse energy per particle. ^{3}He exhibits strong anomalies, i.e. particular high $E_\perp$-values with respect to tritons and α - particles for the heaviest Au+Au system.

A model dependent way was proposed for extracting the equation of state at lower energies than was done earlier (see for example ref. [15]), down to densities $\rho / \rho_0 = 1.5$. The results are another confirmation of a model employing a rather stiff equation of state, which is already tested with data on collective flow and on pion production. It is necessary, however, to point out several problems which must be addressed for a more quantitative discussion; i) the model which has been used to deduce the thermal energy from experimental pion yields assumes a global thermal equilibrium over the whole participant volume and calculates the temperatures in the moment of chemical freeze-out of the π/Δ -degree of freedom, whereas the measured proton transverse energies are influenced also by the clustering to composite particles which increases the temperature of the thermal bath. However, based on measured abundance ratios [4,10] and assuming ideal thermalization in the moment of particle freeze-out one can estimate this effect to cause a maximum increase of the transverse particle energy of about 15-20 % at the lowest bombarding energy and to be less important ($\leq$10 %) at the highest bombarding energy, studied here. ii) A certain part of the transverse momentum may be transmitted via Coulomb repulsion from the large number of protons in the participant volume, and iii) experimentally, the calibration and detector inefficiencies at the highest bombarding energies may introduce some additional uncertainties. Recently, it has also been suggested that a consideration of the momentum dependent interactions in theories used so far, may affect the sensitivity of the information obtained from pion yields to the EOS quite strongly [12].

First results on 60 and 200 AGeV oxygen and sulphur induced reactions indicate a remarkable longitudinal and transverse energy transfer to the target spectator. The excitation energy is comparable to a fireball formed in head on collisions of Au+Au at top Bevalac energies and is sufficient to completely desintegrate the target nucleus into light fragments.

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