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COLLECTIVE FLOW IN MULTIFRAGMENTATION INDUCED BY RELATIVISTIC HELIUM AND CARBON IONS

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Multiple emission of intermediate-mass fragments has been studied for the collisions of p, ^{4}He and ^{12}C on Au with the 4π set-up FASA. In the case of ^{12}C (22.4 GeV) + + Au and ^{4}He (14.6 GeV) + Au collisions, the deviations from a pure thermal break-up are seen in the energy spectra of the emitted fragments, which are harder than those from both model calculations and measured for p-induced collisions. This difference is attributed to a collective flow with the expansion velocity on the nuclear surface about 0.1 c (for $^{12}\mathrm{C} + \mathrm{Au}$ collisions).

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

Коллективный поток в процессе мультифрагментации, вызванный релятивистскими ионами гелия и углерода

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Множественная эмиссия фрагментов промежуточной массы была исследована с помощью 4π-установки ФАЗА для соударений p, ^{4}He, $^{12}\mathrm{C} + \mathrm{Au}$. Для случая ^{12}C (22,4 ГэВ) + Au и ^{4}He (14,6 ГэВ) + Au в энергетических спектрах вылетающих фрагментов видны отклонения от чисто теплового распада: средние энергии фрагментов превышают расчетные значения и измеренные величины для $p + \mathrm{Au}$ взаимодействий. Это различие приписывается коллективному потоку со скоростью, равной $\sim 0,1$ с на поверхности ядра (для $^{12}\mathrm{C} + \mathrm{Au}$ взаимодействия).

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Nuclear multifragmentation is a decay mode of very excited nuclei in which Intermediate Mass Fragments (IMF, $3 \leq Z \leq 20$) are copiously emitted. These findings have been strongly

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stimulated by the idea that this process might be related to a liquid-gas phase transition in nuclear matter. A recent status on multifragmentation can be found in Ref. 1.

There are two ways to produce highly excited nuclei: heavy ion collisions at intermediate energies and reactions induced by light relativistic projectiles. In the first case, nuclear heating is accompanied by compression, fast rotation and shape distortion which may cause dynamic effects in the multifragment disintegration and it is not easy to disentangle all these effects and extract information on thermodynamic properties of hot nuclear systems. The situation becomes more transparent if light relativistic projectiles (protons, helium ions) are used. In this case, dynamic effects are expected to be negligible. Another advantage is that all the fragments are emitted by a single source: a slowly moving target remainder. Its excitation energy might be almost entirely thermal. Light relativistic projectiles provide therefore a unique possibility to study «thermal multifragmentation». It has been shown that thermal multifragmentation indeed takes place in collisions of light relativistic projectiles (p, $\bar{\text{p}}$, ^{3}He, α) with a heavy target [2–9].

In this Letter we concentrate on studying energy spectra of the emitted fragments as they reflect, due to the «Coulomb law», the geometry and dynamics (expansion) of the emitting source. By comparing our results from p+Au [4] collision with those from reactions induced by α particles and ^{12}C projectiles with incident energies of (1 – 4) A·GeV, we evidence a transition from a pure statistical process («thermal multifragmentation») to a behaviour reflecting dynamics. It will be shown that a spatial distribution of the fragments at freeze out can be inferred from the observed additional collective energy.

The experiments were performed with beams from the JINR synchrophasotron in Dubna using the modified [10] 4π-set-up FASA [11]. The device consists of two main parts: (i) Five ΔE (ionization chamber) $\times$ E (Si)-telescopes, which serve as a trigger for the read-out of the system allowing measurement of the charge and energy distributions of IMF's at various angles from 24° to 156° and cover together a solid angle of 0.03 sr. (ii) The fragment multiplicity detector consisting of 64 CsI(Tl) counters (with thicknesses around 30 mg·cm^{-2}) which covers 89% of 4π. This device gives the number of IMF's in the event and their spatial distribution. A self-supporting Au target of 1.5 mg/cm^2 thickness was located in the centre of the FASA vacuum chamber ($\sim$ 1 m in diameter). The following beams were used: protons at energies of 2.16, 3.6 and 8.1 GeV, ^{4}He at energies of 4 and 14.6 GeV and ^{12}C at 22.4 GeV. The average beam intensity was $7 \cdot 10^8$ particles/spill for protons and helium and $1 \cdot 10^8$ particles/spill for carbon projectiles with a spill length of 300 ms and a spill period of 10 s. See also [4] reporting on the p+Au experiment.

The kinetic energy of fragments is determined by four terms: thermal motion, Coulomb repulsion, rotation, and collective expansion of the system at freeze out, $E = E_{\text{th}} + E_{\text{C}} + E_{\text{rot}} + E_{\text{flow}}$. The additivity of the first three terms is quite obvious. For the last term, its independence of others may be considered only approximately when the evolution of the system after the freeze-out point is driven only by the Coulomb force. The Coulomb term is significantly larger than the thermal one as was shown in Ref. 7 for ^{4}He (14.6 GeV)+Au collisions, where the Coulomb part of the mean energy of the carbon fragment is three times larger than thermal one using volume emission of fragments from a diluted system.

The contribution of the collective flow for the p+Au collisions at 8.1 GeV energy was estimated in Ref. 4. It was found that $v_{\text{flow}} < 0.02$ c. This was done by comparing the measured IMF spectra with the ones calculated within the framework of the Statistical Multifragmentation Model (SMM) [13], which includes no flow. For heavy ion collisions, collective flow has been observed and it is the most pronounced in central Au+Au collisions [15]. In this respect, it is interesting to analyse energy spectra of fragments from He+Au and C+Au collisions looking for a possible onset of the collective flow phenomenon.

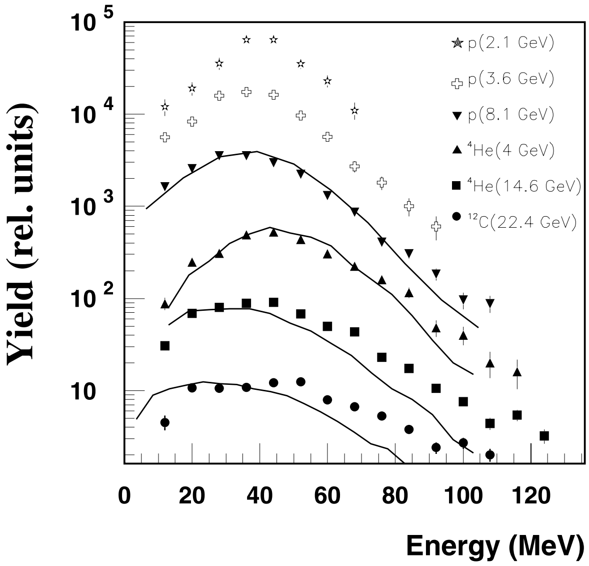

Fig. 1. Energy distribution of carbon isotopes obtained for different collision systems at $\theta = 89°$. The lines are calculated in INC+Exp+SMM model assuming no flow

A comparison of the energy spectra of outgoing carbon isotopes from proton-, helium- and carbon-induced collisions on an Au target is presented in Fig. 1. The spectral shapes show an increase in the number of high energy carbon fragments as the projectile mass is increased. The reaction mechanism for light relativistic projectiles is usually divided into two stages. The first one is a fast energy-depositing stage, during which very energetic light particles are emitted and a nuclear remnant (target spectator) is excited. We use a refined version of the intranuclear cascade model (INC) [16]. The second stage is described by the Statistical Multifragmentation Model (SMM), which considers the multibody decay (volume emission) of a hot expanded nucleus. But such a two-stage approach fails to describe the observed IMF multiplicities. An expansion stage is inserted between two parts of calculation. The excitation energies and the residual masses are then fine tuned [4] to get an agreement with the measured IMF multiplicities. The lines in Fig. 1 give the spectra calculated within the framework of the combined model INC+Expansion+SMM. The fragment energies are obtained by the multibody Coulomb trajectory calculations on an event-by-event basis. At the initial state all the charged particles are assumed to have a thermal velocity only (no flow).

The calculated carbon spectrum for p+Au collisions (at 8.1 GeV) is consistent with the measured one. A similar situation occurs with ^{4}He+Au collisions at 4 GeV, but not with ^{4}He(14.6 GeV)+Au and ^{12}C+Au interactions: the measured spectra are harder than calculated ones.

The trend from Fig. 1, i.e., increasing mean energies with increasing mass and energy of the projectile, is seen for many emitted fragments. This observation is summarized in Fig. 2, which shows the mean kinetic energies per fragment nucleon as a function of the charge of the detected fragments Z. This figure shows a remarkable enhancement in the kinetic energies for light fragments emitted in He+Au and C+Au collisions as compared to the p(8.1 GeV)+Au case. The calculated values of the mean fragment energies (shown by lines) are obtained with the INC+Expansion+SMM model. The measured energies are close to the calculated ones for p+Au collisions in the range of the fragment charges between 4 and 9. The experimental values for ^{4}He+Au and ^{12}C+Au interactions, however, exceed the calculated ones, which are similar for all three cases.

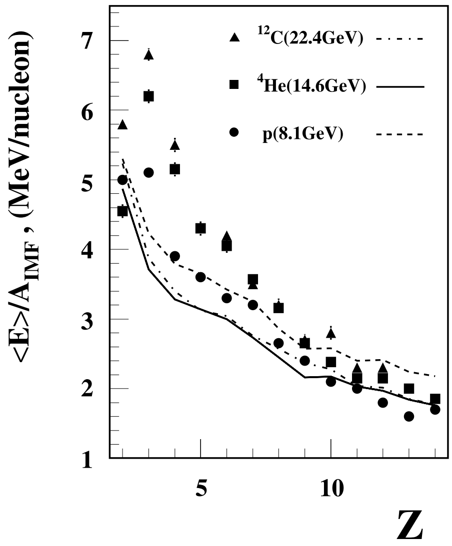

Fig. 2. The mean kinetic energies of outgoing fragments per nucleon measured at $\theta = 89^\circ$ for p(8.1 GeV), ^{4}He (14.6 GeV) and ^{12}C (22.4 GeV) collisions with Au. The lines are calculated within INC+Exp+SMM approach assuming no flow

The observed deviation cannot be attributed to the angular momentum effect. The rotational energy $E_{\rm rot}$ of a fragment with mass A_{IMF} can be estimated from the total rotational energy E_L of a system with mass number A_R using classical rotation:

$$< E_{\rm rot} > /A_{IMF} \cong \frac{5}{3} < \frac{E_L}{A_R} > \frac{< R_Z^2 >}{R_{\rm sys.}^2}, \qquad (1)$$

where R_Z is the radial coordinate of the IMF and $R_{\rm sys.}$ is the radius of the system. According to the INC calculations for C+Au collisions, the mean angular momentum L of the target spectator is $\approx 36\hbar$. It might be reduced by a factor of 1.5 due to the mass loss along the way to the freeze-out point. Finally, $< E_L >$ is estimated to be only 5 MeV and $< E_{\rm rot} > /A_{IMF} \approx 0.04$ MeV/nucleon, which is an order of magnitude smaller than the energy enhancement for light fragments. We conclude that the observed enhancement is caused by the expansion of the system, which seems to be radial, as the $v_\parallel$-versus-$v_\perp$ plot (this will be subject of forthcoming publication) does not show any significant deviation from circular symmetry.

An estimate of the fragment flow energy may be obtained from the difference between the measured IMF energies and those calculated (without any flow). This difference for C+Au collisions is shown in Fig. 3. It shows a drastic decrease of the flow energy with increasing charge of the fragment.

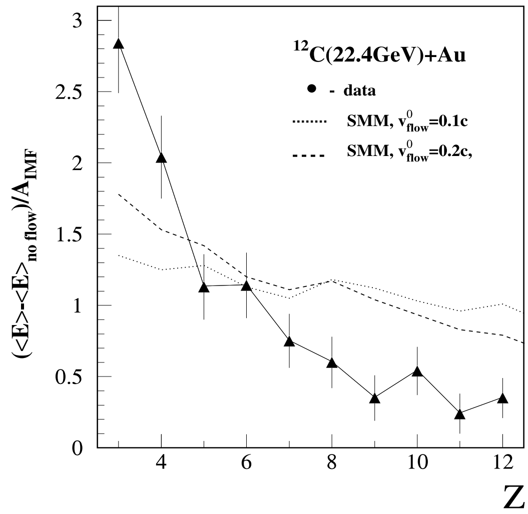

Fig. 3. The flow energy per nucleon (triangles) obtained as a difference of the measured fragment kinetic energies and the values calculated under assumption of no flow in the system. The lines represent calculations assuming a linear profile of the expansion velocity with $v^0_{\rm flow} = 0.1$ c (dotted line), and quadratic profile with $v^0_{\rm flow} = 0.2$ c (dashed line)

In an attempt to describe the data we modified the SMM code by including a radial velocity boost for each particle at freeze out, i.e., the radial expansion velocity was superimposed on the thermal motion in the calculation of the multibody Coulomb trajectories made on an event-by-event basis. A self-similar radial expansion is assumed, where the local flow velocity is linearly dependent on the distance of the particle from the centre of mass. The expansion velocity of particle Z located at radius R_Z is given by the following expression

$$\vec{v}_{\rm flow}(Z) = v^0_{\rm flow} \cdot \frac{\vec{R}_Z}{R_{\rm sys.}}, \tag{2}$$

where $v^0_{\rm flow}$ is the radial velocity on the surface of the system. The use of the linear profile of the radial velocity is motivated by the hydrodynamic models for an expanding hot nuclear system (see for example Ref. 14). The value of $v^0_{\rm flow}$ has been adjusted to 0.1 c in order to describe the mean kinetic energy measured for the carbon fragments. The results are presented in Fig.3 by a dotted line calculated from the difference of the fragment energies obtained for $v^0_{\rm flow} = 0.1$ c and $v^0_{\rm flow} = 0$. The data deviate significantly from the calculated values for Li and Be. It may be caused in part by the contribution of particle emission during the early stage of expansion from the hotter and denser system. It is supported by the fact that the extra energy of Li fragments with respect to the calculated value is clearly seen in Fig. 2 even for the proton-induced fragmentation, where no significant flow is expected. This peculiarity of light fragments has been noted already by the ISIS group for ^{3}He+Au collisions at 4.8 GeV [12].

For fragments heavier than carbon, the calculated curve in Fig. 3 is higher than the data and only slightly decreasing with increasing fragment charge. The trend of the calculation is to be expected. The mean fragment flow energy is proportional to $< R_Z^2 >$ and this value changes only little with fragment charge in the SMM code due to the assumed equal probability of the IMF distribution inside the available break-up volume. The difference between the data and the calculations shown in Fig. 3 indicates that a uniform density distribution is not fulfilled. The dense interior of the expanded nucleus is favourable for the appearance of larger IMF's, if fragments are formed via the density fluctuations. Indications of such an effect could already be drawn from the analysis of the mean IMF energies performed in Ref. 4 for proton induced fragmentation. For p+Au collisions the measured energies are below the theoretical curve for fragments heavier than Ne.

The deviations of the data from the calculations are slightly reduced but still remain, if a quadratic radial profile of the expansion velocity $(\vec{R}_Z/R_{\rm sys.})^2$ is used, as shown in Fig. 3 for $v^0_{\rm flow} = 0.2$ c, which has been chosen to be close to the data at $Z = 6$. The interesting phenomenon of the flow energy reduction for heavier fragments is observed also for the central heavy ion collisions [18]. It is increasingly important at energies ≤ 100 AMeV, and that is in accordance with our suggestion of its relation to the density profile of the hot system at freeze out.

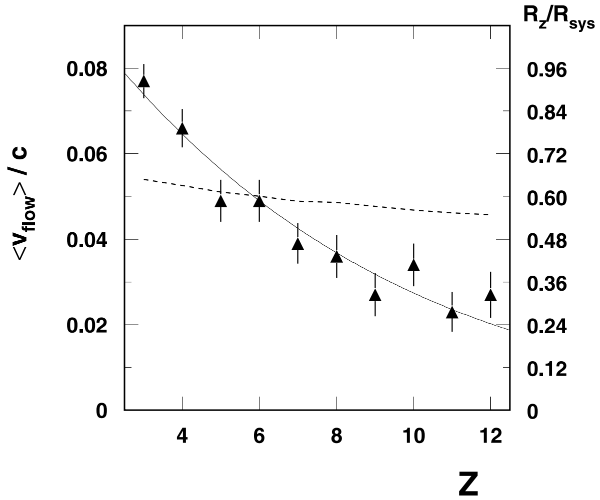

Fig. 4. Experimentally deduced mean expansion velocities (triangles) for $^{12}\mathrm{C} + \mathrm{Au}$ collisions as a function of the fragment charge (left scale), and the mean relative radial coordinates of fragments (right scale), obtained under assumption of a linear radial profile of the expansion velocity. The right scale is chosen to have the value for carbon fragments coincident with that on dotted line which gives $< R_Z/R_{\rm sys.} >$ according to SMM calculations

For the estimation of the mean fragment flow velocities $< \beta_{\rm flow} >$ the difference between the measured IMF energies and calculated ones (without flow) has been used. The results are presented in Fig. 4. The values for Li and Be are considered as upper limits because of the possible contribution of the preequilibrium emission. The corresponding values of $< R_Z > /R_{\rm sys.}$ for the freeze-out point obtained under the assumption of the linear radial profile for the expansion velocity are given on the right-hand scale of this figure. Again, the reduced radial coordinate for the carbon fragment is chosen to coincide with the calculated one. The dashed line shows the mean radial coordinates of fragments according to the SMM code. As has been noted above, the calculated values of $< R_Z > /R_{\rm sys.}$ are only slightly decreasing with Z, as expected from a uniform density distribution, but in clear contrast to the data.

Effects of the radial collective energy for 1 A·GeV Au+C collisions (in inverse kinematics) were considered in [17] by analysing the transverse kinetic energies. The mean radial flow velocities were estimated, but it was done only for fragments with Z$\leq$ 7. In this charge range our analysis gives slightly lower values of the mean expansion velocities as compared to Ref. 17.

The total expansion energy can be estimated by integrating the nucleon flow energy (taken according to Eq. (2)) over the available volume at freeze out. For uniform system one obtains

$$E^{\rm tot}_{\rm flow} = \frac{3}{10} A_R \cdot m_N \; (v^0_{\rm flow})^2 \; (1 - r_N/R_{\rm syst.})^5 \tag{3}$$

with the nucleon mass m_N and radius r_N. For ^{12}C+Au collisions it gives $E^{\rm tot}_{\rm flow} \simeq$ $\simeq (100 - 130)$ MeV, corresponding to the flow velocity at the surface of 0.1 c. Similar results are obtained for ^{4}He(14.6 GeV)+Au collisions. The total flow energy of the fragmenting nucleus is four times lower than the thermal one estimated in the INC+Expansion+SMM approach.

Concluding, the energy spectra of IMF's for reactions p+Au at 2.1, 3.6 and 8.1 GeV, ^{4}He+Au at 4 and 14.6 GeV, ^{12}C+Au at 22.4 GeV are compared. While the fragment kinetic energies are well described within the SMM code for p+Au collisions, the model underestimates the kinetic energies of fragments from collisions induced by ^{4}He and ^{12}C projectiles. The additional energy is attributed to collective expansion. However, a linear flow profile fails to describe the variation of flow energies extracted from the measured spectra with the fragment charge. This discrepancy might be caused by the fact that the model assumes a uniform density distribution and, hence, a rather uniform probability distribution of fragments in the freeze-out volume. The data indicate that heavy fragments are predominantly located more in the interior of the nucleus.

The presented study shows that in spite of the success of statistical multifragmentation models, the description of the freeze-out condition might be still too simplified. The energy spectra provide sensitive probes for the source configuration and the emission dynamics. The range of projectiles, from protons to light nuclei, seems to be quite attractive in this respect for showing a transition from «thermal break up» to dynamical disintegration of hot nuclear matter.

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