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Kinetic energy spectra for fragments and break-up density in multifragmentation

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Abstract

We investigate the possibility, in nuclear fragmentation, to extract information on nuclear density at break-up from fragment kinetic energy spectra using a simultaneous scenario for fragment emission. It is found that a decrease of peak centroids for kinetic energy spectra of fragments with increasing excitation energy can be observed at constant low density, which is different from recently published results of Viola et al. [V.E. Viola, K. Kwiatkowski, J.B. Natowitz, S.J. Yennello, Phys. Rev. Lett. 93 (2004) 132701].

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One of the most challenging tasks of nuclear physics in the last decades is the determination of the phase diagram of excited atomic nuclei. Despite the important theoretical and experimental work already done, the problem is far from being solved. From the experimental point of view the localization of nuclear multifragmentation data in the phase diagram requires accurate independent measurements of temperature and density at the break-up stage. While the problem of temperature determination has been solved with acceptable accuracy up to 5–6 MeV [2–5], no satisfactory method to determine the spatial extension of the presumably equilibrated nuclear system at break-up has been proposed. Thus, experiments using light particles interferometry [6] indicate freeze-out densities ranging from less than $\rho_0/10$ to $\rho_0/2.5$ (where ρ_0 is the normal nuclear density); on the other side, statistical [7–11] and dynamical models [12,13] succeed to describe well the available experimental

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data with freeze-out densities in the interval $\rho_0/9$ to $\rho_0/2.5$.

Ref. [1] tries to obtain information on break-up density using kinetic energy spectra of intermediate mass fragments (IMF: $3 \leqslant Z \leqslant 15$) measured in light ion induced multifragmentation of gold, namely ^{4}He + ^{197}Au at 50 MeV/nucleon [14], ^{14}N + ^{197}Au at 20–100 MeV/nucleon [15] and ^{3}He + ^{197}Au at 4.8 GeV bombarding energy [16].

The pattern of IMF kinetic energy spectra led the authors of Ref. [1] to fit the extracted equilibrium sources with a Maxwell–Boltzmann type distribution,

$$\frac{dN}{dK} = (K - V_C') \cdot \exp\left(-\frac{(K - V_C')}{T_s}\right), \tag{1}$$

where K is the kinetic energy of the considered cluster (A_F, Z_F) emitted by the source (A_s, Z_s), V_C' the cluster kinetic Coulomb energy and V_C the Coulomb barrier between the emitted fragments and the residual nucleus,

$$V_C = 1.44 \cdot \frac{Z_F(Z_s - Z_F)}{d(A_F^{1/3} + (A_s - A_F)^{1/3})}, \tag{2}$$

$$V_C' = \frac{A_s - A_F}{A_s} \cdot V_C; \tag{3}$$

T_s is the temperature of the multifragmenting source.

Thus, the interpretation of the behavior of these spectra with the rise of excitation energy is made within a parameterization suitable for sequential particle emission. From Eq. (1) results that a temperature increase will determine a shift of the centroids of the Coulomb-like peaks toward higher values of K together with the broadening of the distribution while a decrease of the Coulomb barrier (by increasing the fragments' centre relative distances expected at low density) will shift the distribution in the opposite direction. Starting from these premises Ref. [1] presents a systematic fit over an important collection of experimental spectra corresponding to an excitation energy interval ranging from 0.9 to 7.9 MeV/nucleon and reaches the conclusion that the displacement of the maximum of dN/dK IMF distributions toward lower energy and observed in the range 2–5 MeV/nucleon is a sufficient evidence in favor of decreasing break-up density down to $\sim \rho_0/3$ with increasing excitation energy.

Both the short time scale characterizing the decay of nuclei with excitation energies exceeding 3 MeV/nucleon and the pattern of fragments' relative velocities indicate that multifragmentation should be treated as a simultaneous process [17,18]. In this framework, do the displacements of peak centroids of kinetic energy spectra reveal a decrease of the nuclear break-up density? We shall demonstrate in this Letter that such displacements are then obtained at constant low density.

To do that we shall use a microcanonical multifragmentation model (MMM) [11] in order to study the excitation energy dependence of the average Coulomb energy associated to the primary fragments at freeze-out and the IMFs kinetic energy spectra. To keep the treatment as intuitive as possible we assimilate primary fragments at break-up with spherical non-overlapping spheres placed in a spherical container (the freeze-out volume) and calculate Coulomb interaction using fragment–fragment interaction,

$$V_{\text{Coulomb}} = 1.44 \sum_{i<j} \frac{Z_i Z_j}{r_{ij}}, \tag{4}$$

where Z_i denotes the charge of the fragment i, r_{ij} stands for the relative distance between two fragments and the sum runs over all fragments of the given configuration such as to avoid double-counting.

For simplicity we assume that for all considered cases the size of the source (^{197}Au) and its break-up density are constant and modify only the excitation energy. As known from the early studies of multifragmentation, the increase of excitation energy induces an increase of both the degree of fragmentation and the thermal energy of the system. A more advanced fragmentation leads to a more uniform population of the available volume and, consequently, to an increase of the total Coulomb energy of the system. However, by increasing the excitation energy, the number of fragments at freeze-out increases much faster than the associated total Coulomb energy which accounts for most of the experimentally detected final kinetic energy. Thus, one expects a reduced increase of the average Coulomb potential experienced by any fragment due to the mean field generated by the other fragments. These effects are illustrated in Fig. 1. In the left panel are plotted the average values of total Coulomb, thermal energies and multiplicity of fragments with $Z \geqslant 3$ as a function of excitation energy for ^{197}Au at the freeze-out density, $\rho_0/5$, while the right panel of Fig. 1

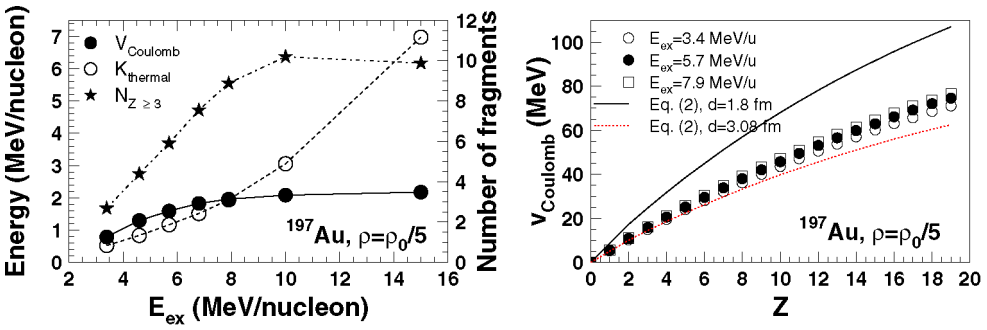

Fig. 1. Left panel: Excitation energy dependence of average values of total Coulomb energy, thermal energy and multiplicity of fragments with $Z \geqslant 3$ as a function of excitation energy for ^{197}Au multifragmenting nucleus at the freeze-out density, $\rho_0/5$ as obtained by MMM; Right panel: Average potential Coulomb energy experienced by a fragment as a function of its charge for ^{197}Au, $\rho = \rho_0/5$ and $E_{\rm ex} = 3.4$, 5.7 and 7.9 MeV/nucleon as calculated with MMM. The Coulomb barrier experienced by a fragment calculated using Eq. (2) is represented with lines assuming that both emitted fragment and residual nucleus have normal nuclear densities ($d = 1.8$ fm) or densities equal to $\rho_0/5$ ($d = 3.08$ fm), see text.

presents the average potential Coulomb energy experienced by a fragment as a function of its charge,

$$v_{\rm Coulomb}(Z) = \frac{1}{2} \cdot 1.44 \sum_{i(Z_i=Z)} Z_i \cdot \sum_j \frac{Z_j}{r_{ij}} \cdot \frac{1}{y(Z)}, \tag{5}$$

where $y(Z)$ represents the average multiplicity of fragments with charge Z. The obvious relation between the total Coulomb energy $V_{\rm Coulomb}$ and the average Coulomb energies experienced by different fragments is,

$$V_{\rm Coulomb} = \sum_Z y(Z) v_{\rm Coulomb}(Z). \tag{6}$$

An increase of about 1.2 MeV/nucleon is obtained for the total Coulomb energy when excitation energy moves from 3.4 to 7.9 MeV/nucleon (left panel) whereas, at the same time, a small increase of about 0.18 MeV/nucleon is observed for example for $Z = 10$ (right panel). The estimation of the Coulomb contribution done using Eq. (2) and $d = 3.08$ fm which corresponds to density $\rho_0/5$ is also shown on the right panel. This value for d is obtained taking $d = 1.8$ for normal density as suggested in Ref. [1]. Estimations are indeed close to average values obtained considering fragment–fragment interactions.

Adding now the kinetic part of the thermal energy at freeze-out shared at random between particles and fragments under constraints of conservation laws, we can consider what is the effect of increasing excitation energy on IMF average kinetic energies. The mean kinetic energy distributions as a function of charge for the same ^{197}Au source and the same density $\rho_0/5$ at $E_{\rm ex} = 3.4$, 5.7 and 7.9 MeV/nucleon are plotted in Fig. 2. At first glance, the behavior of $\langle K \rangle(Z)$ distributions with increasing source excitation is surprising in the sense that while both thermal and Coulomb energies increase, the fragment average kinetic energies decrease. This result can be understood having in mind the strong increase of fragment multiplicity which leads to reduced kinetic energy per fragment. The narrowing of $\langle K \rangle(Z)$ distributions is obviously caused by the narrowing of $y(Z)$ distributions once the excitation energy increases.

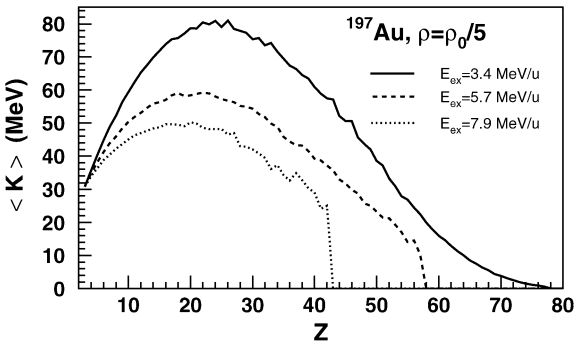

Fig. 2. MMM predictions on break-up average kinetic energy as a function of fragment charge for ^{197}Au source at $\rho = \rho_0/5$ at $E_{\rm ex} = 3.4$, 5.7 and 7.9 MeV/nucleon.

Clearly these results contradict the expectation of an increase with temperature or excitation energy. However they concern average quantities and not the peak centroids. We can consider now the spectra. As

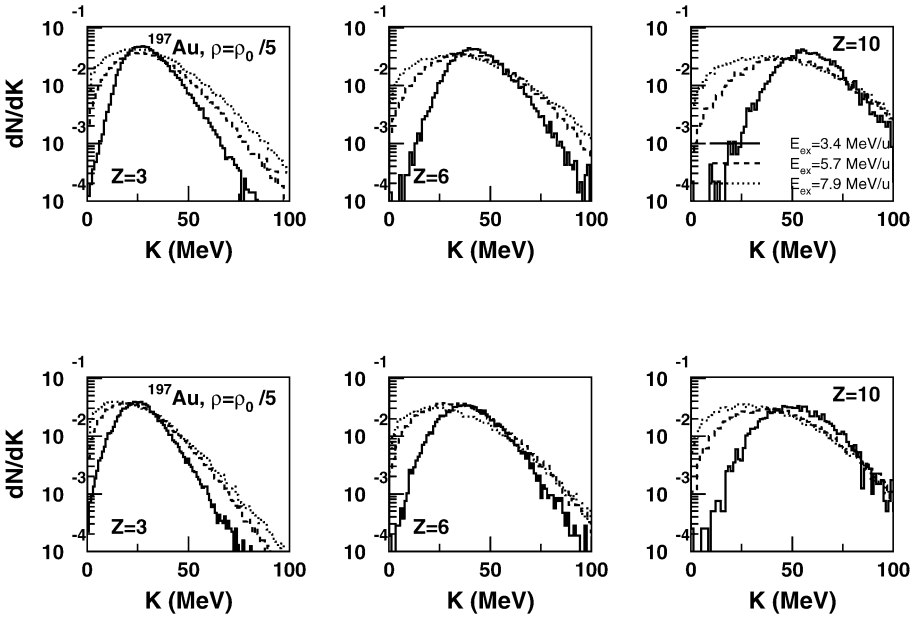

Fig. 3. MMM predictions corresponding to break-up (upper panel) and asymptotic stage (lower panel) kinetic energy spectra for different emitted intermediate mass fragments resulted from the multifragmentation of ^{197}Au at $\rho_0/5$ and different excitation energies.

one may see in the upper panel of Fig. 3 the modification of the IMF kinetic energy spectra is in qualitative agreement with the experimental data cited in Ref. [1]: with increasing $E_{\rm ex}$ the centroids of the distribution move toward smaller energies whereas their widths strongly increase. Since is known that primary excited fragments undergo secondary emission, a natural question is whether or not this process modifies the observed results. As one may see from the lower panel of Fig. 3 sequential evaporations slightly diminish the IMF kinetic energies for a given Z, without modifying the relative displacement of distributions corresponding to different excitation energies.

In conclusion, using a standard simultaneous multifragmentation model we explained the experimentally evidenced evolution of the IMFs kinetic energy spectra with increasing excitation energy as a consequence of advanced system's fragmentation, without any assumption regarding the modification of the break-up density. To make our study as complete as possible, the behavior of both average kinetic energy of IMFs and the IMFs kinetic energy spectra have been analyzed for the freeze-out density range usually addressed by statistical multifragmentation models, namely $\rho_0/7$ to $\rho_0/3$. The obtained results are qualitatively the same as the above presented results corresponding to $\rho_0/5$. This study suggests that an alternative explanation as compared to the conclusions of Ref. [1] can be proposed, which is connected to a different description of multifragmentation. Answering the important question on what is the break-up density dependence on the excitation energy needs more consideration.

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