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Similarity of multi-fragmentation of residual nucleus created in nucleus-nucleus interactions at high energies

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ABSTRACT

Experimental data on multi-fragmentation of residual krypton nuclei created in the interactions of the krypton nuclei with photoemulsion nuclei at energy of 0.9 GeV per nucleon are presented in a comparison with the analogous data on fragmentation of gold residual nuclei at the energy of 10.7 GeV/nucleon. It is shown for the first time that there are two regimes of nuclear multifragmentation: the former is when less than one-half of nucleons of projectile nucleus are knocked out, the later is when more than one-half of nucleons are knocked out. Residual nuclei with closed masses created at different reactions are fragmenting practically simultaneously when more than one-half of nucleons of original nuclei are knocked out. The evidence of existence of a radial flow of the spectator fragment at the decay of residual krypton nuclei is found.

1 INTRODUCTION

Interesting experimental results on nuclear multifragmentation at low and intermediate energies have recently been obtained. The radial spherical symmetrical flow of fragments, or, in other words, the proportionality of the kinetic energy of a fragment to its mass was discovered in central collisions of gold projectile [1-5]. The existence of the flow contradicts the assumption of a stochastic character of the nuclear multifragmentation process. The radial flow of spectator fragments in the rest frame of a fragmenting nucleus has been found at study of projectile gold nuclei interactions with photoemulsion nuclei at energy of 10.7 GeV /nucleon [6,7] According to estimations of Ref.[5], the energy of the radial motion ranges between 30 % and 50 % of accessible energy. At the same time, the another of the remarkable experimental result [8] obtained by the ALADIN collaboration-the constancy of isotope temperature over the wide range of the excitation energy, is treated as an evidence of first order phase transition (liquid-gas) and statistical nature of the nuclear multifragmentation. The third experimental result [9] reported by the INDRA collaboration-the independence of isotope composition of the fragments on the mass of fragmenting nuclei at the same excitation energy, is interpreted as a sign of spinoidal instability of residual nuclei. There is a direct evidence of a perplexing situation.

We believe that the present state of the activity may be settled by studying the fragmentation of light enough systems)in the investigations mentioned heavy systems were analyzed). In fact, the famous statistical multifragmentation model (SMM) [10,11] was in use to describe both heavy nuclei and oxygen residuals fragmentation [12]. No less famous the quantum molecular dynamic model [13], in particular, the quantum antisymmetrized molecular dynamics model [14] which incorporates effects of the mean field, are generally applied to light nucleus induced interactions. Hence, there is an intersection region where two approaches can be applied. The purpose of this chapter is to present the experimental data on multifragmentation of residuals created in 0.9 GeV/nucleon krypton initiated interactions in emulsion.

We start our analysis with the most interesting dependence of multiplicity of intermediate mass fragments (IMF) on the mass of fragmenting system whose measure is the so-called "bound" charge:

$$Z_{bound} = \sum_{F} Z_F \quad , (Z_F \geq 2) \tag{1}$$

or

$$Z_{b3} = \sum_{F} Z_F \quad , \quad (Z_F \geq 3) \tag{2}$$

where Z_F is a charge of a fragment. IMFs have charges $3 \leq Z_F \leq 30$.

Next, we consider intrinsic characteristics of the fragmenting systems such as, the average charge of the largest fragment, asymmetry in the fragment system, etc. Our consideration is summarized in a grief summary.

2 Experimental material

Stacks of NIKFI BR-2 emulsion pellicles were exposed to a 1 A GeV ^{84}Kr beam at the SIS/GSI and a 10.7 A GeV ^{197}Au beam at the BNL/AGS. The sensitivity of the emulsion was not worse than 30 grains per 100 μk for singly charged particles with minimal ionization.

To carry out the analysis, the events induced by krypton nuclei with energy in the interval 0.8-0.95 GeV/nucleon were taken. The mean collision energy for this sample was thus reduced to about 0.9 GeV per projectile nucleon.

All the interactions were found by along-the-track-"fast-slow" scanning with a velocity excluding any discrimination in the event selection. A slow scanning (in backward direction) was made to find the events with unbiased projectile track. After excluding the events of electromagnetic dissociation and purely elastic scattering, a total of 677 krypton-emulsion interactions and 1057 gold-emulsion interactions have been obtained.

Experimentally, the spectator fragments with Z=2 were classified by the visual inspection of tracks. The ionization of such tracks is constant over the whole length and equals $g/g_0=4$, where g_0 is the minimal ionization of singly charged track. Charge assignment for multiply charged tracks were provided by delta-electron density measurements on the length not less than 10 mm. The calibration was made up on known primary tracks and tracks of the double charged fragments. The accuracy of the measured charges was around three charge units for $Z > 40$ and one charge unit for $Z < 20$.

The relativistic particles emitted at $\theta < \theta_0$ (θ is the emission angle) were considered as singly charged fragments. θ_0 is determined as

$$\mathrm{Sin}\theta_0 = 0.2/P_0 \qquad (3)$$

where P_0 is the projectile nucleus momentum per nucleon in GeV/c.

In each investigated event, the polar θ and azimuthal φ angles of all charged particles were measured.

The transverse momentum of a spectator fragment was defined as

$$|P_F| = 2Z_F P_0 \sin\theta \qquad (4)$$

The ratio A/Z for fragments was assumed to equal two. The mean relative accuracy in the transverse momentum of fragments does not exceed 7%.

It should be noted that at high energies in contrast to low and intermediate ones two clear-out distinguishable regions corresponding to the projectile and target fragmentation are observed. The probability of compound nucleus creation is assumed to be small. Thus, the question how to select the fragments of the projectile and target nuclei is simply settled Projectile fragments are regarded to have the velocities equal to that of projectile nucleus Having this mind, the relation (4) was suggested Clearly, it is invalid for deep inelastic collisions where the fragments loss significant parts of their longitudinal momentum. The lack of necessary experimental information and specificity of the photoemulsion experiments prevent this circumstance from being taken into consideration.

The assumption of equality between the number of protons P and neutrons N in the fragments brings main uncertainty to fragment momenta For heavy nuclei (N > P), the relation (4) underestimates the transverse momentum For double charged fragments among which ^{3}He isotopes are presented , the relation (4) overestimates, on average, the transverse momentum. As shown in [15], 10% ^{3}He admixture among all the fragments with Z=2 gives less than 1% growth in the dispersion of the transverse momentum (the dispersion changes from 162 to 164 MeV/c). This result cannot, of course, have any effect on the conclusions of the present chapter

Identification of the target fragments in photoemulsion experiments requires a special track measurement technique that is not used at our studies. Thus our data concern the fragments of projectile nuclei, which were identified by the commonly accepted emulsion analysis procedure. In photoemulsion studies dedicated to high energies (E > 1 A GeV), the projectile fragments are usually called as spectator fragments. We will follow this tradition, sometimes omitting the assignment "spectator".

3 IMF multiplicity dependence on nuclear residual mass

It is obvious that the multiplicity of intermediate mass fragments (N_{IMF}) rises with increasing the excitation energy at a fixed nuclear residual mass. However, at high excitation energies, the production of light fragments gets dominant, and $< N_{IMF} >$ must decrease. It is just the dependence that has been observed by the ALADIN-group [16-18] for multifragmentation of gold residual created in the interactions of the gold projectile with various targets at an energy 600 MeV/nucleon. The "bound" charge Z_{bound} which includes the charges of α-particles was taken as a measure of nuclear residual mass. Since α-particles can be produced at the pre-equilibrium decay stage, another value, Z_{b3} [19], was suggested to be used. The most remarkable result was that $< N_{IMF} >$ as a function of Z_{bound} or Z_{b3} had proved independence of the target mass As the dependence under discussion is essentially determined by a relation between the excitation energy and the nuclear residuals mass, one can conclude that the gold residuals of the same masses from various reactions have nearly the same excitation energies Our results of Fig.1 allows one to make the statement more precise.

Fig.1 displays the IMF multiplicity as functions of Z_{bound} and Z_{b3} (open squares) in the interactions of krypton nuclei with photoemulsion nuclei at energy of 900 MeV/nucleon in a comparison with the analogous data on 10.7 GeV/nucleon gold nuclei interactions (closed circles) [6]. As shown, the data points for Kr and Au nuclear residual fragmentation are close to each other for $Z_{bound} \leq 22$ and $Z_{b3} \leq 16$. Although the error bars for Kr-points are quite large, we can say that at the average IMF multiplicity for Kr projectile is larger than that for gold nucleus at the same value of Z_{bound}. At the same time, the $< N_{IMF} >$ as functions of Z_{b3} for the two projectiles are practically in a coincidence at $Z_{b3} < 16$. This indicates that nuclear residuals of the same masses formed in interactions of different systems at high energies have approximately the same excitation energies if the initial nuclei have lost more than one half of their nucleons at the fast stage of the collisions

We focus attention on the fast growth of our IMF multiplicity in the region of $Z_{b3} \sim 30$ with decreasing Z_{b3}. The rise seems to be related to a threshold character of the nuclear multifragmentation. Clearly, at small excitation energy the process of evaporation of nucleons and light nuclei is dominated. At large excitation energy, the multifragment decay channel opens. It was not clear whether the probability of the last process evolves smoothly with excitation energy increase or whether it is threshold character. It is difficult to note a change in the evolution of IMF multiplicity at large Z_{b3} for gold residuals fragmentation due to large error bars The statistics of the data is not rich enough to give conclusive results. The data of the ALADIN collaboration at $Z_{b3} \geq 70$ have the required statistics but, seemingly, suffer from methodical uncertainties. We believe that a study of IMF multiplicity at large Z_{b3} intended to look for the threshold character of the nuclear multifragmentation is of great interest.

4 Dependencies of intrinsic characteristics of decaying system on Z_{bound} and Z_{b3}

A quite unexpected result was obtained at an analysis of the heaviest fragments. Fig.2 shows the mean charge of the heaviest fragment in an event as a function of Z_{bound} or Z_{b3} (symbols are the same as in Fig.1. One can see a clear change in the dependence of $< Z_{max} >$ on Z_{b3} at $Z_{b3} \sim 17$. The analogous change, but not so pronounced, has been found in the gold residuals fragmentation. This effect is slightly shaded when Z_{bound} is used.

Thus we can conclude that nuclear residuals in different manners when more or less one half of nucleons from the primary nucleus are ejected. The data presented in Fig.3, where the average asymmetry coefficient (A_{12}) as a function of Z_{bound} or Z_{b3} is plotted, confirms the above conclusion.

The value of A_{12} for each event is defined as

$$A_{12} = \frac{Z_1 - Z_2}{Z_1 + Z_2} \quad (5)$$

where Z_1 , Z_2 , etc-the charges of fragments ordered such that $Z_1 \geq Z_2 \geq Z_3$ ....,$Z_1 \equiv Z_{max}$. As seen, there is not any peculiarity in the dependence of $<A_{12}>$ on Z_{bound}. $<A_{12}>$ as a unction of Z_{b3} remains practically constant at $Z_{b3} \leq 17$ and then increases sharply with Z_{b3} - the events with $Z_{b3} \leq 17$ have strong asymmetry A similar behavior is also observed at the fragmentation of heavier systems.

Summing up, we can conclude that there exists at least two regimes of fragmentation.

5 Energy of fragments as functions of Z_{bound} or Z_{b3}

According to the statistical model of nuclear multifragmentation, the kinetic energy of the fragments in the rest frame of fragmenting nucleus is determined by the charge of the residual nuclei. Hence, the decrease of the fragment energies can be expected with decreasing Z_{bound} [20]. Going from the laboratory system to a rest frame of a fragmenting nucleus, we have used the Gallilean transformation described in Ref.[6]. The average kinetic energy of a fragment is connected with its transverse momentum, assuming the isotopic decay, by

$$<E> = \frac{3}{2} \frac{<P_F^2>}{4Z_F m_N} \quad (6)$$

Here, P_F -the transverse momentum of the fragment, Z_F -its charge and m_N -the mass of the nucleon.

Fig.4 presents the mean kinetic energies of the fragments in the events with the number of multiply charged fragments ($Z_F \geq 3$) larger or equal three. One can see that the kinetic energy of Kr fragments has no tendency to be decreased with decreasing the mass of residuals in the region $Z_{bound} \leq$ 25. Moreover, in the region they are practically permanent. A similar behavior is observed at the fragmentation of gold residuals. The results provide an evidence for the radial flow of the fragments, with the energy of the flow depending on the mass of the initial nucleus (according to our data). The used symbols are, closed circles for the interactions of krypton nuclei with photoemulsion nuclei and open circles for the interactions of gold nuclei with photoemulsion nuclei.

6 Summary

The experimental data on the multifragmentation of the krypton residual nuclei formed in the interactions with photoemulsion nuclei at energy 0.9 GeV/nucleon are presented.

The mechanism of the nuclear residual fragmentation is shown to be practically independent on the mass of projectile nucleus if Z_{bound} does not exceed a one half of the charge of the initial nucleus.

The evidence are obtained that the multifragmentation is of a threshold character and that there is a radial flow of the fragments that depends upon the mass of the initial nucleus.

The experimental regularities manifest themselves more brightly when the value Z_{b3} is used as a measure of the residual mass.

Further experimental and theoretical studies of the multifragmentation of intermediate mass nucleus are of interest.

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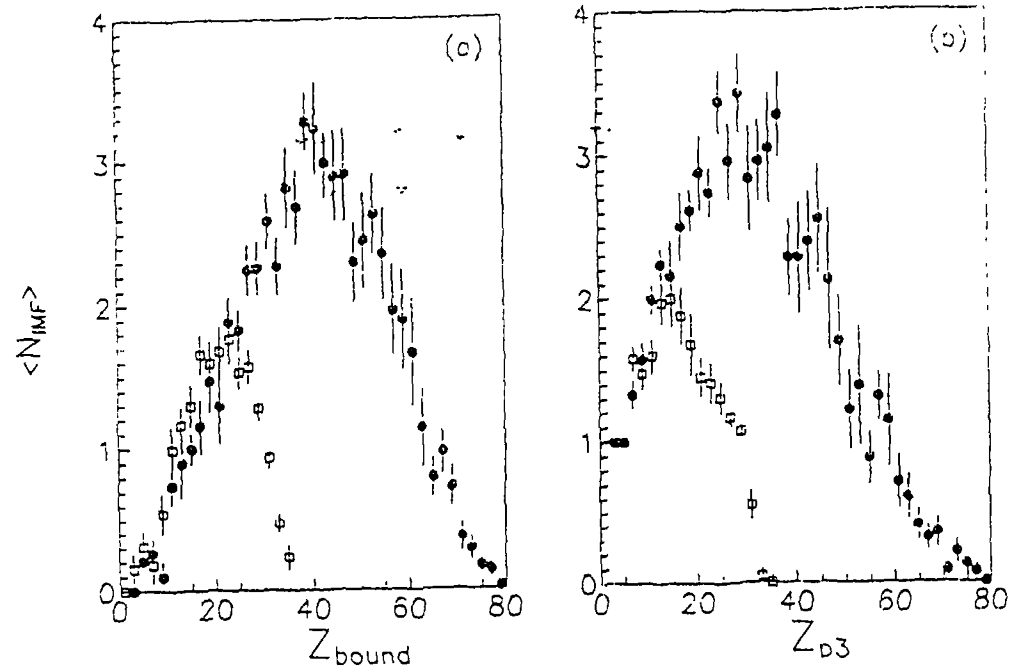

*Fig.*1: The dependencies of the IMF multiplicity on Z_{bound} (a) and Z_{b3} (b). Open squires-data for Kr interactions at E=900 MeV/nucleon, closed circles-data for Au interactions at E=10 7 GeV/nucleon

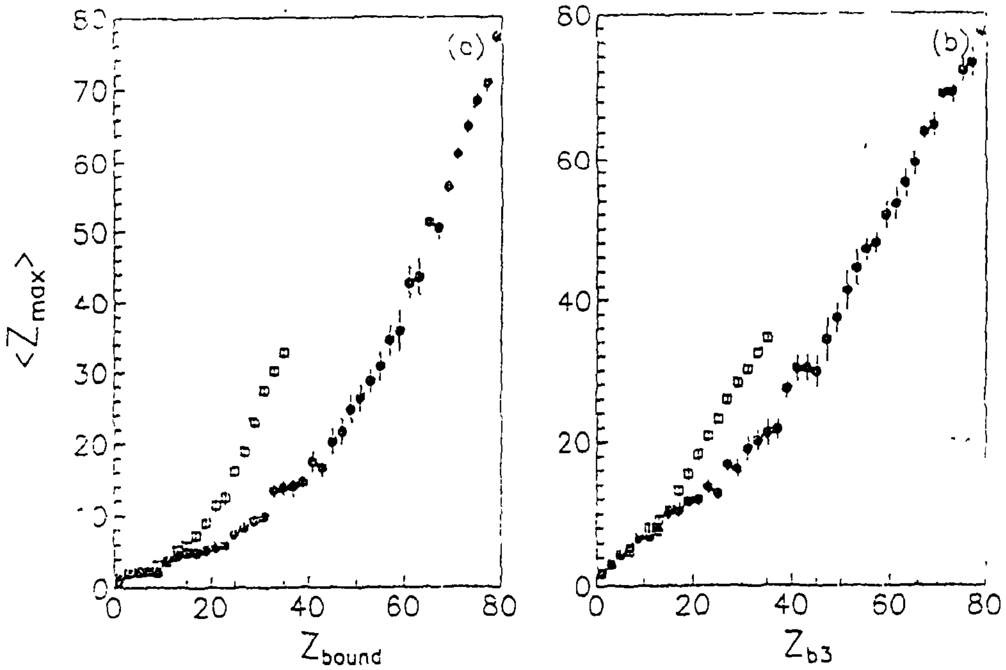

Fig.2: The average charge of the largest fragment in the events as a function of "bound" charge Symbols are the same as in Fig 1

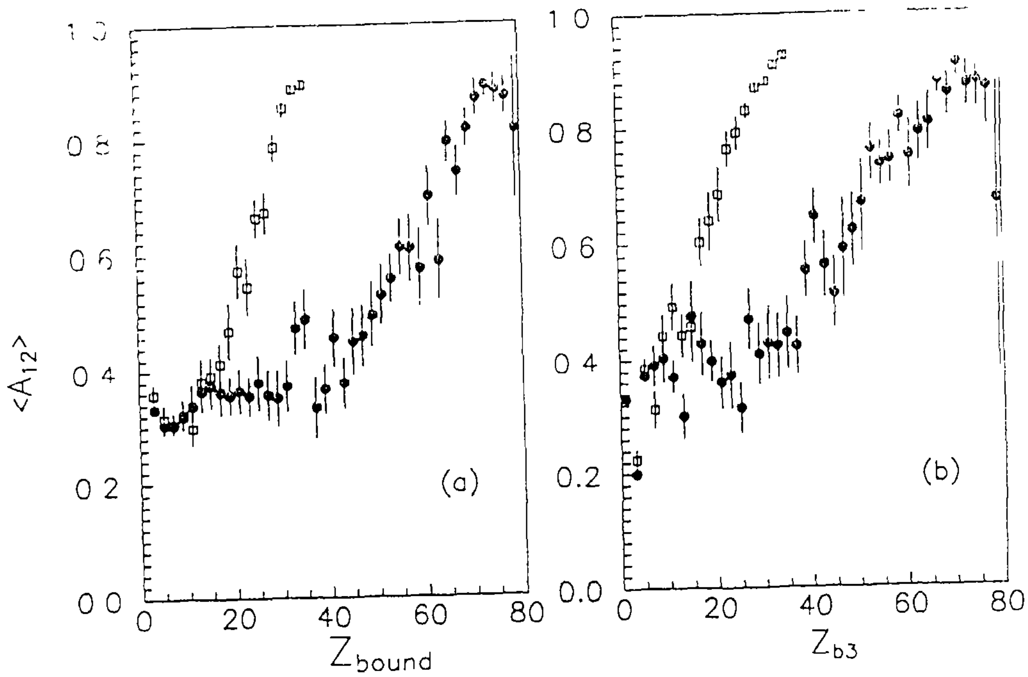

Fig.3: The average coefficient of asymmetry in the measured events as a function of "bound" charge Symbols are the same as in Fig 1

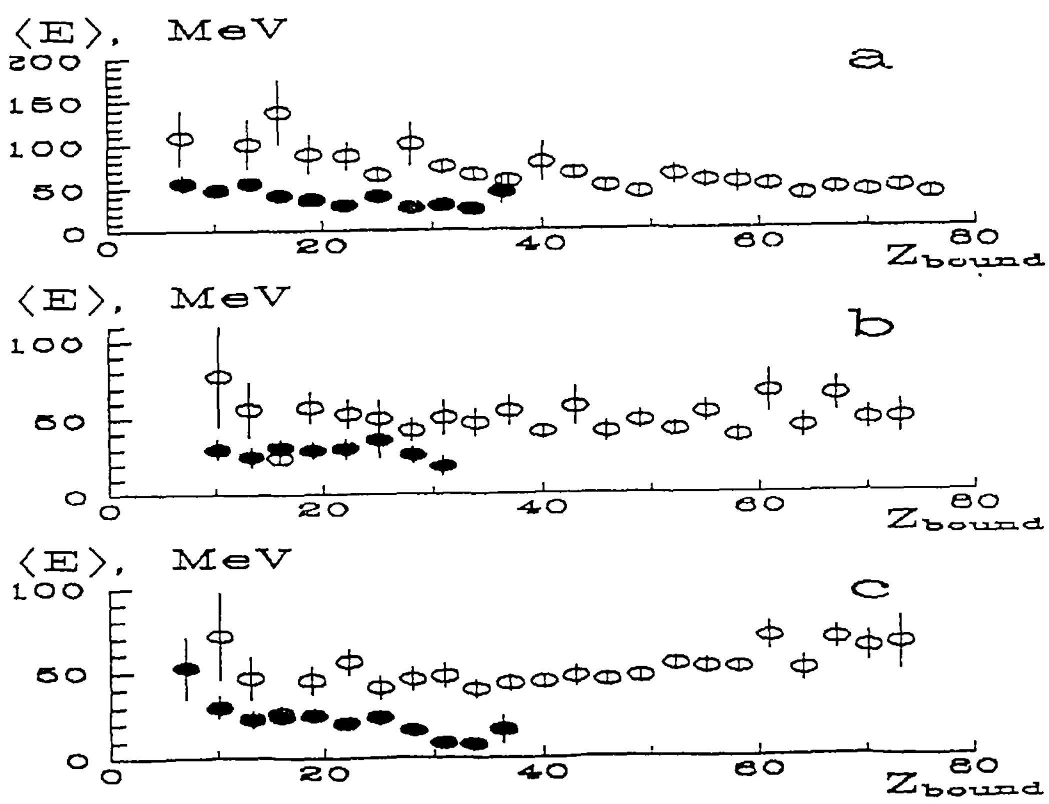

Fig.4: The estimated average kinetic energy of the fragments in the rest frame of the fragmenting nucleus Symbols are the same as in Fig 1 a)- energies of double charged fragments, b)- energies of the fragments with $Z_f = 3 - 5$, c)- energies of IMFs