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DECAY OF HOT NUCLEI PRODUCED BY RELATIVISTIC LIGHT IONS

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Распад горячих ядер, образующихся в реакциях с легкими релятивистскими ионами

Установлено, что в соударении легких релятивистских ионов (p, ^{4}He) с тяжелой мишенью (Au) образуются сильновозбужденные ядра, распадающиеся путем множественной эмиссии фрагментов промежуточной массы (ФПМ). Средние множественности ФПМ равны (в пределах ±15%) 2,0, 2,6 и 3,0 при использовании протонов с энергией 2,16, 3,6 и 8,1 ГэВ соответственно. Эти значения близки к тем, что получаются на пучках тяжелых ионов в том же диапазоне энергий. Этот факт рассматривается как указание на то, что средняя множественность ФПМ не чувствительна к динамике соударений, а определяется фазовым объемом конечного состояния. Энергетические спектры фрагментов описываются статистической моделью мультифрагментации, предполагающей расширение ядра перед развалом. Оценена средняя скорость расширения в момент распада ядра: $v_{exp} \leq 0{,}02$ c. Среднее время жизни фрагментирующей системы (≤ 75 fm/c) получено из анализа угловой корреляции фрагментов для соударений ^{4}He (14,6 ГэВ) +Au. Эти результаты отвечают сценарию «тепловой» мультифрагментации.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Decay of Hot Nuclei Produced by Relativistic Light Ions

In collisions of light relativistic projectiles (p, ^{4}He) with heavy nuclei (Au) very excited target spectators are created, which decay via multiple emission of intermediate mass fragments. It was found that the mean IMF multiplicities are equal (within 15%) to 2.0, 2.6 and 3.0 at proton energies 2.16, 3.6 and 8.1 GeV respectively. These values are comparable with those obtained with heavy ions in the same beam energy range. This is considered to indicate that this observable is not sensitive to the collision dynamics and is determined by the phase space factor. IMF energy spectra are described by the statistical model of multifragmentation neglecting dynamics of the expansion stage before the break up. The expansion velocity is estimated to be ≤ 0.02 c. The mean lifetime of a fragmentating system is found to be ≤ 75 fm/c from IMF-IMF-angular correlations for ^{4}He (14.6 GeV) +Au collisions. The results support a scenario of true «thermal» multifragmentation.

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

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Introduction

The investigation of decay of very hot nuclei has become a topic of great interest. Largely it is concentrated on the process of multiple emission of intermediate mass fragments (IMF, $3 \leq Z \leq 20$). It is now established as a main decay mode of highly excited nuclei, and this process is likely to occur when a nucleus has expanded and lower density is reached [1]. It is under debate whether this process is related to a liquid-gas phase transition in nuclear matter [2–4].

The common way to produce very hot nuclei is to use reactions induced by heavy ions at energies $30 \div 100$ MeV/n. But heating in this case is accompanied by compression, strong rotation and shape distortion, which cause the so-called dynamic effects in the nuclear decay. It seems difficult to disentangle all these effects to get information on thermodynamic properties of a hot nuclear system. The picture becomes more clear when light relativistic projectiles are used [5,6]. One should expect that dynamic effects are negligible in that case. All the IMF's are emitted by the only source — a target spectator, and decay of this hot nucleus proceeds in an apparently statistical manner ("thermal multifragmentation"). Similar advantages are given by antiproton beams of energy (1-2) GeV [7]. Light projectiles allow complementary information to that gained from heavy ion collisions and comparison will make it possible to reveal the influence of compression and rotation on the multifragment decay of a hot nucleus.

In this paper we present the experimental results for the multifragment emission induced by relativistic protons (up to 8.1 GeV) and alphas (at 3.65 GeV/n).

Experimental setup

The experiments were performed at the JINR synchrophasotron in Dubna using the new 4π-setup FASA. Now we have two versions of this device: one (FASA-1) [8] was used in the experiments with a ^{4}He-beam. The main parts of the device are (i) a fragment multiplicity detector (FMD) consisting of 55 thin CsI(Tl) detectors which cover a major part of 4π; the FMD gives the number of IMF's and their space distribution; (ii) five time-of-flight telescopes (TOF), which measure energies, velocities and masses of fragments at different angles and serve as a trigger for the read-out of the system; (iii) a position sensitive parallel-plate avalanche counter (PPAC) for measuring the angular and velocity distributions of IMF's detected in coincidence with TOF's. A selfsupporting ^{197}Au target 1.0 mg/cm^2 thick was used. The average beam intensity was $5 \cdot 10^8$ part./spill (one spill of 300 ms per 10 s).

In the experiments with a proton beam the other version of FASA was used, in which the TOF's are replaced by ΔE(ion.chamber)-E(Si(Au))-telescopes. The PPAC is replaced by CsI(Tl) detectors and the total number of counters in the FMD is increased to 64. The plexiglass light guides in FASA-1 are replaced by empty ones covered with diffuse reflector (MgO). This change has significantly improved the background in the FMD, which is connected with Cherenkov-radiation created by the beam halo in plexiglass light guides. The mean value of the background in the FMD of FASA-2 was less then 2%. The efficiency of scintillators for fragments was calculated taking into account the response of CsI-films to heavy ions [8], the energy spectra and charge distribution of IMF measured by telescopes. For the threshold used (two times the pulse height of ^{241}Au α-particles) the IMF-efficiency is 52%, while the admixture of the fragments with Z = 2 is $\approx$ 3% in respect to IMF's.

Fragment multiplicity in p + ^{197}Au collisions

Experiments have been performed at beam energies 2.16, 3.6, 8.1 GeV and intensity around 10^9 p/spill. The telescopes are located at angles 24°, 68°, 87°, 112° and 156°. The measured multiplicity distributions associated with trigger fragments in the range $6 \leq Z \leq 20$ are shown in Fig. 1a.

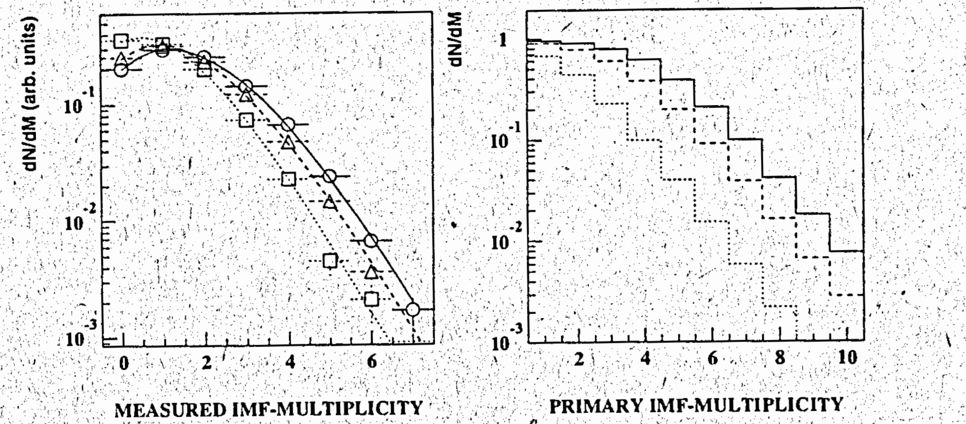

Fig. 1. Left: Measured IMF-multiplicity distributions associated with a trigger fragment of charge $6 \leq Z \leq 20$ for p+Au collisions at 8.1 GeV (circles, solid line), 3.6 GeV (triangles, dashed line), 2.16 GeV (squares, dotted line). They are fitted with Fermi-like distributions (right picture), folded with the experimental filter.

These distributions differ significantly from the primary ones because of the experimental filter. To deduce the primary multiplicity one should make correction for the FMD efficiency, for the effect of double hits in the scintillators. Furthermore, one has to take into account the fact that the readout is triggered by telescopes with a small solid angle ($\sim 5 \cdot 10^{-2}$ sr.), so the trigger probability is proportional to the IMF multiplicity. All these effects are combined in a response matrix (experimental filter). The mean primary multiplicity is determined by fitting the parametrized distribution, folded by the experimental filter, to the experimental one. A reasonable assumption should be made for the shape of the primary distribution. In the case of definite excitation energy the multiplicity distributions are well described by the Poisson function with mean value decreasing as the impact parameter increases [9]. In the present experiments we deal with fragmentation events averaged over the full range of impact parameters. Having this in mind we assumed the primary IMF-multiplicity distribution to be shaped like a Fermi distribution. Figure 1b presents the primary multiplicity distributions, which correspond to the best fit to the measured ones. The mean values $< M_{IMF} >$ (for events with at least one IMF) are 2.05±0.30, 2.6±0.4, 3.06±0.45 for the beam energies used. Corrections for double hits (both below and above the threshold) do not change $< M >$ by more than several percent but improve the fit at the tail of the multiplicity distribution. The errors (15%) are significantly larger than statistical ones reflecting the uncertainties in the FMD-efficiency.

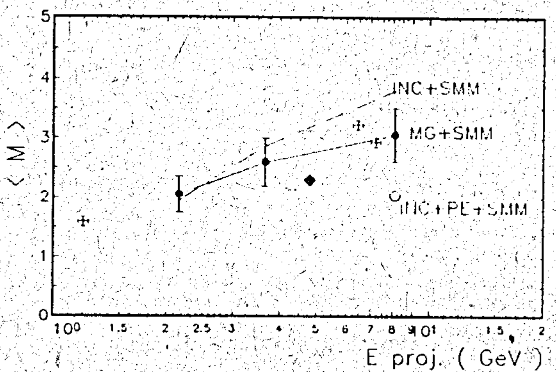

Fig. 2. The mean IMF-multiplicities for the events with at least one IMF as a function of the beam energy. Solid points are for p+Au collisions, diamond is for ^{3}He+Au, crosses are for heavy-ion-induced fragmentation. The lines are calculated by MG+SMM and INC+SMM. The open point is calculated assuming preequilibrium emission after intranuclear cascade.

Figure 2 shows the mean multiplicities as a function of projectile energy together with some published data on multifragmentation, induced in Au-target by ^{3}He(4.8 GeV) [10] and heavy ions. It is interesting to compare the values of $< M_{IMF} >$ obtained with relativistic light projectiles and heavy ions. The published data were reanalyzed in a proper way to get $< M_{IMF} >$ for the events with at least one IMF, averaged over the whole range of impact parameters. The data used are ^{40}Ar (30 MeV/n)+ Au [11], ^{129}Xe(50 MeV/n)+ Au [9], ^{12}C(600 MeV/n)+ Au [12]. The IMF multiplicities for proton-induced reactions are close to those obtained with heavy ions. So, this observable is not sensitive to the reaction dynamics and, one should think, it is determined mainly by the space phase factor of the final state.

The reaction mechanism for the light relativistic projectiles is divided into two steps. The first one consists of a fast energy deposition stage, during which very energetic light particles are emitted and the nuclear remnant (spectator) is excited. The second, slower step of the reaction is decay of a target spectator. The fast stage is usually described by the intranuclear cascade model (INC). We use a version of the INC from ref. [13] to get the distributions of the nuclear remnants in the charges, masses, excitation energies and momenta. The second stage is described by the statistical multifragmentation model (SMM). We use a version of the SMM from [14]. Evidence for the statistical behaviour of a target spectator will be presented in the next chapter: angular distributions of IMF and their energy spectra at different angles are well described in the framework of the statistical decay of a thermalized moving source. Within the SMM the probabilities of different decay channels are proportional to their statistical weights. The break-up volume determining the Coulomb energy of the system is taken to be $V_b = (1+k)A/\rho_o$, where A is the mass number of the decaying nucleus, ρ_o is the normal nuclear density, k is a model parameter. So, thermal expansion of the system before the break-up is assumed. The primary fragments are hot, and their deexcitation is taken into account to get final IMF distributions. In the further calculations we used $k = 2$ based on our analysis of the correlation data [26].

The upper dashed line in Fig. 2 is obtained by means of this combined model (INC + SMM). It is drawn through the calculated values of $< M_{IMF} >$ at three beam energies. The calculated mean multiplicity for the highest energy is 25% larger than the experimental one. So, the cascade model overestimates the excitation energy of the residual nucleus. For the lowest beam energy the calculated $< M_{IMF} >$ coincides with the measured one.

The use of the preequilibrium exciton model (PE) [15] together with the INC gives the mean multiplicity 33% less than the experimental value for $E_p = 8.1$ GeV. It means that inclusion of preequilibrium emission results in underestimation of the excitation energy. One can conclude that the use of the INC or INC+PE does not solve a problem of describing the properties of a target spectator for a wide range of projectile energies, so one should look for an alternative approach. The authors of [16] used some phenomenological distributions to describe ALADIN data. Unfortunately, due to the phenomenological nature of the approach there is no simple way to extend their results to other combinations of projectile/target. Therefore, to describe charge, mass and energy distributions of the residual nuclei we used as a basis the well known Glauber theory [17] being in a good agreement with the experimental data on elastic and inelastic hadron-nucleus ($hA-$) and nucleus-nucleus ($AA-$) interactions at intermediate and high energies. The Glauber theory, as it is, however, provides only distribution of "wounded" (knocked out) nucleons resulting from the primary collisions of the projectile nucleons with the target ones and does not take into account the secondary interactions of ejected nucleons. To take such interactions into consideration a phenomenological approach was used [18] motivated by the Reggeon theory of $hA-$ and $AA-$interactions. That approach taking into account the so called "enhanced diagrams" (see [19] for details) provides an alternative to the cascade approach to secondary particle interactions. The full implementation of Reggeon picture is rather complicated but roughly it can be reproduced by ejecting additional nucleons placed not far in the impact parameter plane from the primary ejected ones. So that the knock out of the nucleons with impact parameter $\vec{s}$ initiates the knock out of the neighboring nucleons with impact parameters $\vec{s}_j$ with probability $\phi(|\vec{s}-\vec{s}_j|)$. The second nucleon, in its turn, can initiate a knock out of a third nucleon with ptobability $\phi(|\vec{s}_j-\vec{s}_k|)$ and so on. The probability function $\phi(|\vec{s}_j-\vec{s}_k|)$ was chosen in Gaussian form to reproduce Regge behaviour of the simplest enhanced $hA-$interaction diagram. The parameters of the function were determined from the data on g-particles multiplicities in inelastic interaction of 3.6 GeV/nucleon protons and nuclei with light and heavy components of emulsion. The space coordinates of the primary ejected nucleons are determined with the aid of DIAGEN code implementing exact Glauber relations for $pA-$ and $AA-$interactions [20]. This approach was successfully applied to the analysis of the nuclear destruction at the fast stage of the interaction in the high energy AA collisions [18].

To calculate the excitation energy of the nuclear residual we suppose that each spectator (not ejected) nucleon placed at a distance less than 2 fm from a nucleon touched at the fast stage of the interaction receives an energy distributed as

$$P(\epsilon)d\epsilon = \frac{1}{<\epsilon>} e^{-\epsilon/<\epsilon>} d\epsilon .$$

A sum of the energies transferred to the spectator nucleons gives the excitation energy. The quantity $<\epsilon>$ is treated as a fitting parameter. Below we will refer to that combined approach as a modified Glauber approach (MG). Within this model followed by SMM the mean IMF-multiplicities were calculated varying the values of $<\epsilon>$. The best fit to the experimental data is obtained for $<\epsilon>$ equal to 6, 8 and 10 MeV at the beam energies 2.16, 3.6 adn 8.1 GeV respectively. Fig. 3 shows the energy distributions of residual nuclei calculated for $E_p = 2.16$ and 8.1 GeV. For all inelastic events the mean excitation energies are 164 and 279 MeV respectively. But for the events with IMF emission mean excitation energies are equal to 574 and 780 MeV. Only harder collisions lead to multifragmentation.

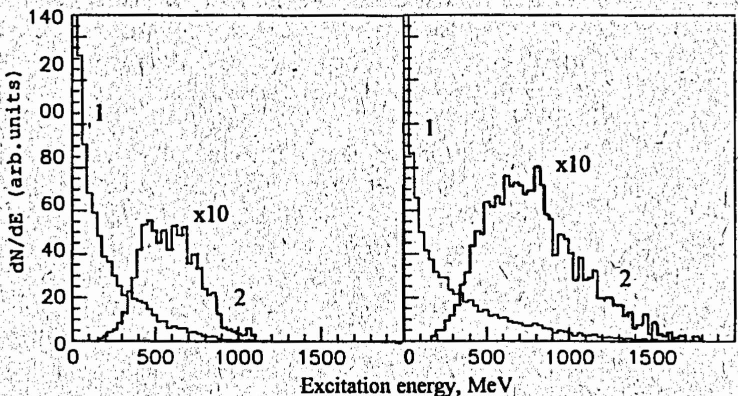

Fig. 3. The calculated distributions of the excitation energy for the target spectators, obtained with a modified Glauber approach for p+Au collisions at 2.16 GeV (left) and 8.1 GeV (right): 1 — for all residual nuclei, 2 — for events with IMF emission.

All the data are summarized in Table 1. The residual excitation energies calculated with MG+SMM model are lower than estimated with INC+SMM. Note that the mean charge and mass number of fragmenting nucleus grow with the decrease of the beam energy in INC+SMM model. The opposite tendency is for MG+SMM calculations. For projectile energy 2.16 GeV both models give the same values for $< M_{IMF} >$, but Z and A of fragmenting nuclei differ significantly. These very different predictions can be judged by measuring IMF-energies, as they are determined by the charge and size of the source.

Table 1:

Reaction	Experiment	Calculations					Model
	$< M_{IMF} >$	$< M_{IMF} >$	Z_{MF}	A_{MF}	$\bar{E}^*_{MF} MeV$	$\bar{E}^*_R MeV$	
p+Au		3.8	70	168	930	524	INC+SMM
8.1 GeV	3.06±0.45	2.05	50	122	528	204	INC+PE+SMM
		3.13	67	165	780	279	MG+SMM
p+Au	2.6±0.4	2.9	73	175	782	407	INC+SMM
3.6 GeV		2.6	65	162	677	225	MG+SMM
p+Au	2.05±0.30	2.0	75	181	660	328	INC+SMM
2.16 GeV		2.03	64	157	574	164	MG+SMM

1. Z_{MF}, A_{MF}, $\bar{E}^*_{MF}$ are the mean charge, mass number and excitation energy of the fragmenting nucleus.
2. $\bar{E}^*_R$ is the mean excitation energy of all residual nuclei after the fast stage of collision.
3. INC is the intranuclear cascade, SMM is the statistical multifragmentation model, MG is the modified Glauber approximation.

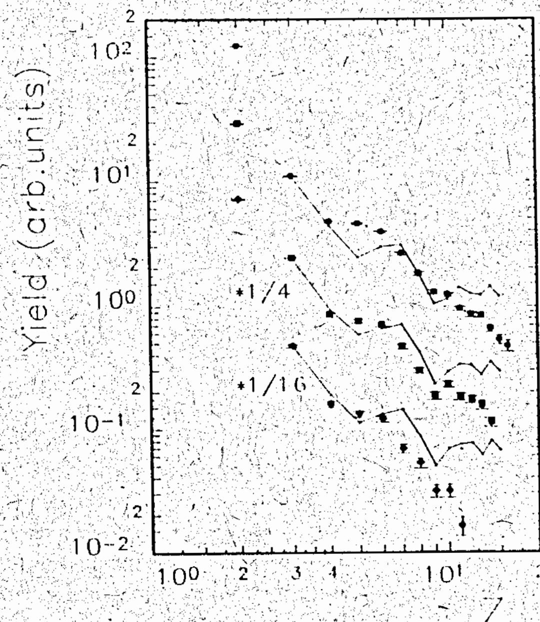

Fig. 4. Charge distributions for IMF's created in the p+Au collisions at 8.1 GeV (top), 3.6 GeV (middle) and 2.16 GeV (bottom). The broken lines are calculated by the combined MG+SMM models, normalized at Z = 3.

Charge distributions and energy spectra of IMF

Charge distributions of IMF for three beam energies are presented in Fig. 4 together with calculated curves obtained with MG+SMM model. The model description resembles the data for $3 \leq Z \leq 10$, but for heavier fragments it is slightly overestimating. Empirical dependence $Y(Z) \sim Z^{-\alpha}$ fits the data well (excluding the yield for Z = 2) with α equal to 2.30 ± 0.12, 1.90 ± 0.10 and 1.86 ± 0.10 for the beam energies 2.16, 3.6 and 8.1 GeV. These values are close to reported ones in [21]. The weak variation of the charge distributions with beam energy can be considered as an indication of a slight change in the target spectator temperature with increasing E_p in the range from 2 to 8 GeV.

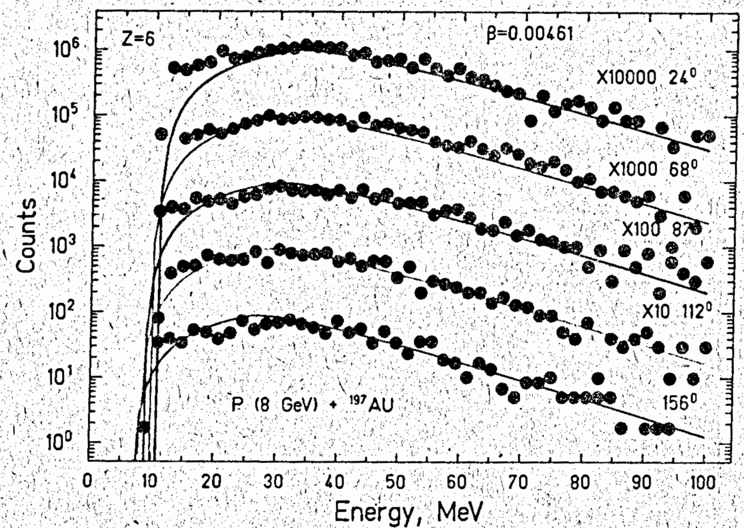

Fig. 5. The energy spectra at different polar angles for carbon produced in p+Au collisions at 8.1 GeV. Spectra are fitted by the Maxwellian distribution for equilibrated moving source.

Figure 5 shows the energy spectra of carbon at different angles measured for the beam energy 8.1 GeV. They are fitted by the empirical function suggested first in [22] and modified in [23]. It is a smeared Maxwellian distribution shifted by an effective Coulomb barrier ($E_c \pm \Delta$). Particles are emitted isotropically in a system moving forward (in the beam direction) with a velocity $\beta_{||}$. Variation of the spectrum with angle is entirely determined by velocity transformation from the moving frame to the laboratory one. All the spectra are fitted with the same set of parameters: E_c = 19 MeV, $\Delta = 20$ MeV, $\beta_{||} = 0.0046 \pm 0.001$ and $T_S = 14$ MeV (slope parameter). The angular distributions (Fig. 6) are slightly anisotropic and can also be explained in the picture of the isotropic decay of the moving source. This analysis gives grounds for the statement that the IMF-emission proceeds as a decay of a thermally

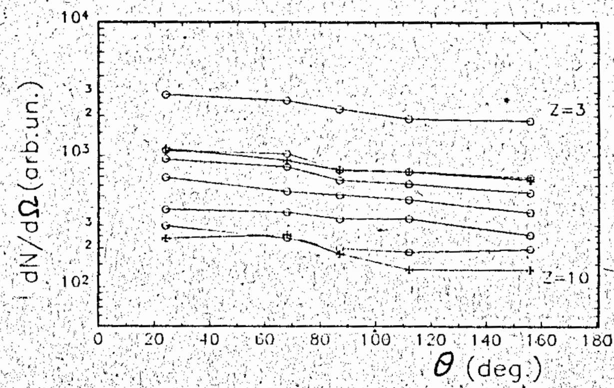

Fig. 6. Angular distributions for fragments with $3 \leq Z \leq 10$ from p(8.1 GeV)+Au collisions.

From the point of view of the statistical model of multifragmentation this parametrization of the IMF-spectra is not obvious. In the SMM one considers prompt partition of the excited nucleus into fragments. At the first moment they have a Maxwellian energy distribution determined by the temperature of the system. The final energy distribution results mainly from the Coulomb repulsion of the system (volume emission). Figure 7 presents comparison of the carbon spectrum from p(8.1 GeV)+ Au collisions with calculated ones. The experimental spectrum is a sum of the spectra measured at 68°, 87° and 112°. The calculations were performed applying SMM to the excited remnants arising from MG calculations. Figure 8 presents the comparison of the mean energies of IMF's per nucleon (for p+Au at 8.1 GeV) with values calculated by the modified Glauber approximation and SMM. The theoretical values coincide with the experimental ones within the error bars. The statistical model assumes that the break-up of the system proceeds after expansion, driven by a thermal pressure. The freeze-out volume is taken to be $3V_o$, and the expansion velocity v_{exp} is neglected. So, the comparison of the measured IMF energies with the calculated ones is the way to estimate v_{exp}. In our case the effect of the expansion velocity is not visible and only the upper limit of the collective energy and velocity can be extracted:

$$E_{exp} \leq 0.2 \text{ MeV/n}, \quad v_{exp} \leq 0.02 \text{ c.}$$

The mean IMF-energies for $E_p = 3.6$ ns 2.16 GeV are close to those presented in Fig. 8. This observation is in accordance with MG+SMM calculations and in contrast to results obtained by INC+SMM model, which predicts increasing IMF-energies when the beam energy goes down from 8.1 to 2.16 GeV.

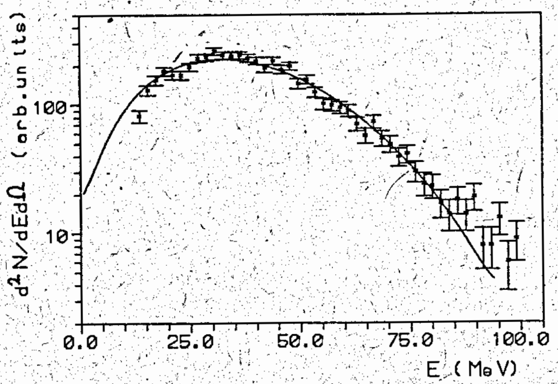

Fig. 7. The energy spectrum for carbon emitted in p(8.1 GeV) + Au collisions. The line is calculated by the modified Glauber prescription and statistical multifragmentation model.

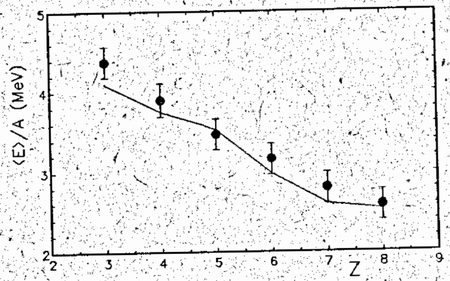

Fig. 8. The IMF-mean energies for the p(8.1 GeV)+Au reaction. The line is calculated by the modified Glauber approximation and statistical multifragmentation model.

On the time scale of IMF emission

The time scale of the IMF emission is a key characteristic for understanding the multifragmentation phenomenon: is it a "slow" sequential process of independent emission of IMF's or is it a new decay mode with "simultaneous" ejection of the fragments governed by the total accessible phase-space? "Simultaneous" means that all fragments are liberated at freeze-out during a time, which is smaller than a characteristic Coulomb time τ_c. For that case emission of IMF's are not independent, they interact via long-range Coulomb forces during acceleration in the electrical field after freeze-out. According to [24], $\tau_c \approx 10^{-21}$ s. Measurement of the emission time for IMF's (τ_{em} is a mean time delay between two consecutive fragment emissions) is a direct way to answer the question on the nature of the multifragmentation phenomenon.

To extract the time scale of thermal multifragmentation we measured and analyzed the relative angle IMF-IMF correlations for ^{4}He+Au collisions at 3.65 GeV/n.

The relative angle distribution exhibits a minimum at $\theta_{rel} = 0°$ arising from the Coulomb repulsion between fragments. A magnitude of this effect drastically depends on the time scale of the emission, since the longer the time interval between fragments, the larger their space separation and the weaker Coulomb repulsion.

The measured relative angle distribution is shown in Fig. 9 [26]. To describe it a classical multi-body Coulomb trajectory calculations was done with varying the mean lifetime of a fragmenting system (τ) as a parameter. The initial configurations (fragment charges and masses, positions and momenta) were taken from the statistical multifragmentation model. Having in mind the model dependence of such analysis, we did it with two different codes for the trajectory calculations and two variants of the SMM [25, 26]. The results obtained are similar. The best fit of the theoretical and measured distributions corresponds to the prompt decay. The point at $\theta_{rel} = 25°$ is more sensitive to τ. To estimate the upper limit for τ at a high confidence level we take three standard deviations at that point and get $\tau \leq 75$ fm/c. The emission time is related to the mean lifetime by an equation:

$$\tau_{em} = \frac{\tau}{< M_{IMF} > -1} \sum_{n=1}^{<M>-1} 1/n \,.\ \text{So,}\ \tau_{em} \leq 50\ \text{fm/c}.$$

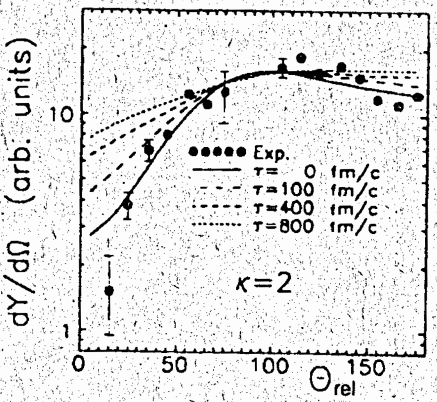

Fig. 9. Distribution of relative angles between IMF's, created in ^{4}He (3.65 GeV/n) + Au. Selection on Z values: $3 \leq Z_1 \leq 15$, $6 \leq Z_2 \leq 15$. The curves are calculated for 4 values of the mean lifetime of the fragmenting system.

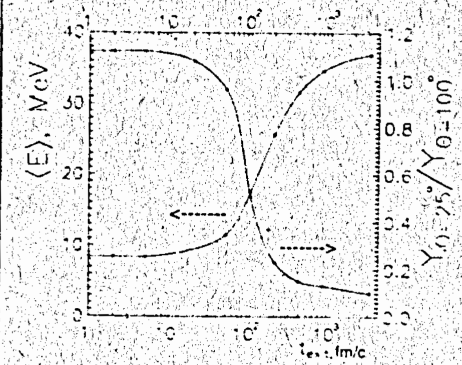

Fig. 10. The mean kinetic energy of a fragment ($Z = 6 \div 7$) and the magnitude of the small angle suppression as a function of the acceleration time.

Figure 10 shows evolution of the fragment ($Z = 6\div7$) kinetic energy and depth of the Coulomb minimum (for IMF's with $12 < A \leq 30$) as a function of the time after the break-up moment. It was calculated with $\tau = 0$. At the beginning the fragment mean energy E_o is determined by nuclear temperature which is around 5.5 MeV. The final energy is mainly Coulomb one in origin. The time dependence of fragment energy can be approximated by the formula: $E_f = E_o + E'_c(1 - exp(-t/\tau_c))$, where τ_c is "Coulomb time". According to the present calculations, $\tau_c = 220$ fm/c. The emission time is significantly less then τ_c, hence the independent sequential emission of intermediate mass fragments is definitely excluded.

Conclusion

1. In collisions of light relativistic projectiles with a heavy nucleus very excited target spectators are created, which decay via multiple emission of intermediate mass fragments.

2. The mean IMF multiplicities for proton-induced fragmentation of Au-target at the beam energies $2\div8$ GeV are comparable with those obtained with heavy ions. It may be considered as an indication that this observable is not sensitive to the reaction dynamics and is determined mainly by the space phase factor.

3. The multiplicities, charge and energy distributions of IMF's are described in the framework of combined model, which includes the modified Glauber approach for the fast stage of reaction and the statistical multifragmentation model, neglecting dynamics of the expansion stage.

4. The mean lifetime of a fragmenting system for ^{4}He(3.65 GeV/n)+Au is found to be ≤ 75 fm/c. It was done by an analysis of angular IMF-IMF correlations.

The present results support a scenario of true thermal multifragmentation of a hot and expanded nuclear system.

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