Isotopic Composition of Fragments in Nuclear Multifragmentation

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Abstract

The isotope yields of fragments, produced in the decay of the quasiprojectile in Au+Au peripheral collisions at 35 MeV/nucleon and those coming from the disassembly of the unique source formed in Xe+Cu central reactions at 30 MeV/nucleon, were measured. We show that the relative yields of neutron-rich isotopes increase with the excitation energy in multifragmentation reaction. In the framework of the statistical multifragmentation model which fairly well reproduces the experimental observables, this behaviour can be explained by increasing $N/Z$ ratio of hot primary fragments, that corresponds to the statistical evolution of the decay mechanism with the excitation energy: from a compound-like decay to complete multifragmentation.

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Nuclear fragmentation and its connection to the behaviour of nuclear matter at high excitation energy is the subject of intensive theoretical and experimental investigations [1]. Some general properties of this process are already established: at relatively small excitation energies ($E^* \leq 2–3$ A MeV) there is a formation and decay of a long–lived compound-like nucleus system. This process can be described by evaporation/fission–like models. At higher excitation energies (close to the binding energy) there is a complete fast disintegration of the system into fragments. In this case statistical models based on the hypothesis of a nuclear phase transition (simultaneous decay) happen to be very successful [2,3].

The parameters of the nuclear system at the break-up have been studied by many methods (see e.g. [4]). Information about the density in the freeze-out volume is usually extracted from the analysis of velocity correlation functions and kinetic energies of fragments. The temperature of the system can be deduced from different observables: 1) relative populations of unstable nuclear levels, 2) fragments’ kinetic energies, or 3) relative production of isotopes. The last method, based on the statistical properties of double isotope ratios [5], seems to be the most reliable one, and in fact for the first time it made possible to obtain a nuclear caloric curve as an experimental evidence of a nuclear liquid-gas type phase transition [6].

Usually these methods need a correction for secondary decay of hot fragments produced in the freeze-out volume [7]. It has to be stressed that the information about chemical composition of hot fragments is of primary importance: depending on their $N/Z$ ratio, the decay can in fact proceed differently. Moreover the knowledge of the chemical composition of the primary fragments would allow to more precisely establish the thermodynamical conditions at the freeze-out, e.g., to provide a way to apply the energy balance [8], as well as it allows to obtain unambiguous data to extract excitation energies of fragments via correlation analysis [9]. Furthermore it can hint for behaviour of the symmetry energy term of the nuclear Equation of State at subnuclear densities and make difference between dynamical and statistical mechanisms of fragmentation [10].
In this paper we present recent data on the isotope production in heavy-ion collisions at intermediate energies \cite{11,12} with the aim of studying the isotope content of fragments for different sources and excitation energies during the transition from the low energy decay to the multifragmentation. We’ll show that the behaviour of the experimental isotope yields as a function of source size, isospin and excitation energy can be connected to the corresponding evolution of the \(N/Z\) ratio of the hot fragments, leading to more insight in the freeze-out condition.

We investigated the Xe+Cu at 30 MeV/nucleon and Au+Au at 35 MeV/nucleon reactions. The experiments were performed at the National Superconducting K1200 Cyclotron Laboratory of the Michigan State University. The angular range \(3^\circ < \theta_{\text{lab}} < 23^\circ\) was covered by the MULTICS array \cite{13}. The identification thresholds in the MULTICS array were about 1.5 MeV/nucleon for charge identification and about 10 MeV/nucleon for mass identification. The MULTICS array consisted of 48 telescopes, each of which was composed of an Ionization Chamber (IC), a Silicon position-sensitive detector (Si) and a CsI crystal. Typical energy resolutions were 2%, 1% and 5% for IC, Si and CsI, respectively. Light charged particles and fragments with charge up to \(Z=20\) were detected at \(23^\circ < \theta_{\text{lab}} < 160^\circ\) by the phoswich detectors of the MSU Miniball hodoscope \cite{14}. The charge identification thresholds were about 2, 3, 4 MeV/nucleon in the Miniball for \(Z=3, 10, 18\), respectively. The geometric acceptance of the combined array was greater than 87\% of \(4\pi\).

The multiplicity of detected charged particles (\(N_c\)) was used for the reduced impact parameter \(\hat{b}\) reconstruction:

\[
\hat{b} = \frac{b}{b_{\text{max}}} = \left( \int_{N_c}^{+\infty} P(N'c) dN'c \right)^{1/2}.
\]

Here \(P(N_c)\) is the charged particle probability distribution and \(\pi \cdot b_{\text{max}}^2\) is the measured reaction cross section for \(N_c \geq 3\).

The decay products coming from the decay of the quasiprojectile in peripheral Au+Au 35 MeV/nucleon reaction and those coming from the disassembly of the unique source formed in Xe+Cu 30 MeV/nucleon central collisions have been identified through a care-
ful data selection taking into account for the experimental efficiency distortions on energy and angular distributions [11,12]. In particular it has been verified that all the detected decay products are emitted nearly isotropically from the same source and that their energy distributions have Maxwellian shapes, i.e. that angular and energy distributions are compatible with a statistical emission, providing an experimental indication that thermalization has been reached [11,12]. The reconstruction of excitation energies of the sources was carried out analyzing kinematic characteristics of the produced fragments (calorimetric evaluation [8,13]).

We studied fragments coming from the excited quasiprojectile Au-like sources produced in peripheral Au+Au collisions with impact parameters $0.95 < \hat{b} > 0.5$, corresponding approximately to excitation energies from 3 to 6 MeV/nucleon. Also we considered central ($\hat{b} < 0.2$) Xe+Cu collisions which provide sources with excitation around 5.5 MeV/nucleon with approximately the same number of nucleons as Au but with larger charge (the thermal source can be considered as a system after total fusion of colliding nuclei in the center of mass system). In ref. [11,12] these data were used to obtain a caloric curve. The double isotope ratio method allows to eliminate the need of the knowledge of the initial $N/Z$ value of the source, and provides estimates for the temperature. To get information about the composition of hot fragments, new observables should be studied, such as the isotope yields for fixed elements and their evolution with the excitation energy and other parameters of the emitting source. We think that an analysis of the relative isotope production can provide a more reliable information about statistical picture of the process than an analysis of the isobars. The neighbouring isobars (with $\Delta Z=1$) might be produced at different Coulomb barriers, the difference being up to 10 MeV for the Au source. The uncertainty in accounting the real Coulomb energy of the isobars in the freeze-out may essentially exceed the difference in their binding energy ($\sim 1$ MeV) that prevents to conclude unambiguously about thermodynamical parameters.

To avoid a possible problem of preequilibrium in the emission of light charged particles we concentrate mainly on IMFs in this study. In fig. 1 we show the relative isotope yields versus excitation energy obtained from the experimental data for Au sources (each
isotope yield is normalized to the total yield for fixed $Z$ value). The relative yields change a little as function of the energy, however, one can see a very interesting feature: the relative yields of isotopes with big $N/Z$ ratios become larger with increasing excitation energy. In fig. 2 we present the ratios of yields of measured isotopes with the biggest and smallest number of neutrons at fixed $Z$ values versus the excitation energy. For all analysed IMFs, the ratio increases considerably in the energy range of $E^*=3$–6 MeV/nucleon. Within such range, the lowest energy corresponds to the onset of multifragmentation with mean IMF multiplicity around one plus a heavy residual, while at the highest energy the fragmentation into many IMFs dominates. Looking at the sources with different $N/Z$ ratios we found that the abundances of neutron-rich isotopes are larger for the peripheral quasiprojectile Au than for the central Xe+Cu unique source, at the same excitation energy of about 5.5 MeV/nucleon. The relative yields at this excitation energy are shown in fig. 3. This trend has a natural explanation as the $N/Z$ ratio of the Au source is larger than the Xe+Cu one.

If we assume that the yields of the observed isotopes are mainly affected by the secondary decay of hot primary fragments having a slightly larger size, one can consider the presented data for the Au source as an experimental evidence that the $N/Z$ ratio of intermediate mass primary fragments increases with the excitation energy of the source. However the physical process behind of this evolution needs a clarification.

It was shown that the statistical multifragmentation model (SMM) very well reproduces the observed charge yields and the $He-Li$ isotope temperatures, as well as the mean fragment kinetic energies. In the following we use the set of SMM parameters which gives the best description of multifragmentation of the sources produced in peripheral collisions. The freeze-out density was taken $1/3\cdot\rho_0$ ($\rho_0$ is the normal nuclear density). The crucial condition for the present isotope analysis is the requirement of a full description of the charge yields for each considered charge distribution. Under this condition the same parameterization for the central Xe+Cu collisions was used. A possible slight decrease of the source size, as a result of preequilibrium emission, does not affect the conclusions because it hardly changes the $N/Z$ ratio of the source; likewise a small
dynamical expansion effect has minor importance. We have checked that the calculated isotope trends (see below) remain stable with respect to reasonable variations of the SMM parameters in the ranges where the charge yields and other observables are reproduced.

We performed a detailed analysis of the isotope production in the framework of this statistical model. Comparison of the SMM predictions with the data is shown in fig. 1, 2 and 3. The qualitative agreement is evident (even quantitative for some important isotopes) and the general trends, especially, the increase with excitation energy of the neutron-rich isotopes with respect to the neutron-deficit ones, are correctly reproduced. However there are few discrepancies in the results which require some justification. In the SMM the Fermi-break-up model is used to describe the secondary decay of fragments with $A \leq 16$. It takes into account all ground and nucleon-stable excited states of light fragments and calculates the probabilities of population of these levels microcanonically (according to the available phase space). It does not include matrix elements of the transitions between these states that can be important at small excitation energies. Also the model does not take into account for possible shifts of the nuclear states caused by Coulomb interaction of the excited fragments with the surrounding nuclear matter: these shifts should be calculated in consistent quantum theories. However, in our cases we have a rather high excitation energy of hot primary IMFs: from 2 to 3 A MeV and higher, that is considerably larger than thresholds of the main break-up channels, and the above mentioned problems do not affect the calculated trends. Obviously one can better see the $N/Z$ effect in yields of nuclides far from $\beta$-stability line, which are less influenced by the shell structure.

According to the SMM predictions at the beginning of multifragmentation the number of primary nucleons in the freeze-out is very small and nearly all available protons and neutrons are bound in hot primary fragments. Their $N/Z$ ratio depends on the fragment size. If there are light and heavy fragments in the freeze-out, the light fragments have typically smaller $N/Z$ ratio than the heavy ones: these channels are more energetically favorable because of an interplay of the symmetry and Coulomb energies. In fig. 4 we show how the mean $N/Z$ ratios for the light ($Z = 8 - 10$) and heavy ($Z = 68 - 70$)
primary fragments evolve with the excitation energy. It is interesting to note that, if a
big (residue-like) hot fragment is present in the freeze-out, its $N/Z$ ratio can be even
larger than the corresponding source ratio because the other light fragments have a con-
siderably lower ratio. At excitations around the multifragmentation threshold ($E^\ast_{\text{thr}}$ =3-4
MeV/nucleon) big fragments start to disappear and nearly all available neutrons are com-
bined into hot IMFs giving rise to their neutron content. Finally at very high excita-
tions ($E^\ast \sim$8 MeV/nucleon) the $N/Z$ ratio of the hot IMFs starts to decrease because the
number of primary free neutrons increases hastily. This behaviour is responsible for the
corresponding trends of the cold fragments produced after deexcitation of these primary
IMF (see in Fig.4, e.g., $Z=5$). Mainly as a consequence of this evolution, we observe an
increase of the $N/Z$ ratio of the cold fragments in the energy range $E^\ast$=3–6 MeV/nucleon,
and a sizeable change in the relative yields of neutron-rich and neutron-deficit isotopes
(see figs. 1, 2). At higher energies this ratio should drop similarly to the hot fragment one.

We should point out that different mechanisms are responsible for the fragment pro-
duction in the SMM. At small excitation energy light IMFs can be emitted from a
compound-like nucleus system. It favours the production of nearly symmetric isotopes
with large binding energy (close to $\beta$-stability line). Therefore their $N/Z$ ratios are usu-
ally smaller than the ratio of the source. The probability of the evaporation of IMF is
small, however, it contributes to the yield at $E^\ast \leq E^\ast_{\text{thr}}$. At excitation energies higher
than the threshold the multifragmentation sets in: from a fast break-up into two hot frag-
ments it evolves towards the break-up into three or more fragments with the increase of
the source excitation energy \[2\]. At the multifragmentation the secondary decay of hot
primary fragments is the main process defining a relative abundance of particular iso-
topes. In the SMM calculations the contribution of the evaporated isotopes favours the
low ratios presented in fig. 2 at small $E^\ast$. However, assuming that only the evaporation
mechanism exists at high excitations (independent from the reproduction of the charge
yield) the observed increase of the ratio can not be explained. That supports the suggested
evolution of the decay mechanisms and isotope composition of hot fragments.
It was shown in Ref. [17] that an increase of the $N/Z$ source ratio leads to increasing the relative yields of neutron-rich isotopes, in agreement with present results. In their analysis they extract also information about neutron-to-proton ratio ($n/p$) at the freeze-out. In the present calculations with SMM we found that for central (Xe + Cu) and peripheral (Au) sources with the excitation of 5.5 A MeV this ratio increases more than increasing the $N/Z$ ratio of the corresponding sources, in agreement with [17]. A possible production of neutron-rich hot primary fragments is also predicted by other theoretical models. Dynamical stochastic mean field calculations [10] for Au source predict hot fragments with the same $N/Z$ ratio as the SMM. Also an analysis of the correlation functions performed in [9] comes to the conclusion that the larger neutron content of the hot primary fragments corresponds to the experimental data.

In summary, we presented new data on yields of isotopes produced after decay of the Au and Xe + Cu sources at excitation energy range of 3–6 MeV per nucleon, that is around and slightly above the multifragmentation threshold. We found that the experimental relative yields of neutron–rich isotopes increase with excitation energy for the Au sources. The SMM calculations reproduce the whole set of data well enough to support the statistical picture realized in this model. In this approach the energy dependence of the isotopic composition of the produced fragments can be explained in terms of a transition from an evaporation-like emission of few fragments to the total multifragmentation break-up which leads to the increase of neutron content of hot primary intermediate mass fragments.

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Figure captions

**Fig.1:** Relative yields of isotopes of different elements versus excitation energy of Au source. Symbols are experimental data, lines are SMM calculations: $^6$Li, $^7$Be, $^{10}$B, $^{11}$C (open circles, dashed line); $^7$Li, $^9$Be, $^{11}$B, $^{12}$C (full circles, solid line); $^8$Li, $^{10}$Be, $^{12}$B, $^{13}$C (open squares, dot-dashed line); $^{14}$C (full squares, dotted line). The experimental uncertainties on the excitation energy are the same as shown in fig. 2; error bars on relative yields are smaller than symbols size.

**Fig.2:** Ratio of relative yields of neutron-rich to neutron-deficit isotopes of Li, Be, B and C fragments versus excitation energy of Au source. Solid circles are the experi-
mental data, while lines refer to SMM calculations; solid squares refer to central Xe+Cu experimental data.

**Fig.3:** Relative yields of different isotopes for fragments with charges from $Z=1$ to $Z=6$. Circles are experimental data: the solid ones are for the Au system, the open ones are for the Xe+Cu system at the excitation energy of 5.5 MeV/nucleon. Solid and dashed lines are the corresponding SMM calculations.

**Fig.4:** The SMM calculations of the mean neutron-to-proton ($N/Z$) ratio of hot primary fragments produced at the freeze-out (full lines) and the cold fragments produced after the secondary decay (dot-dashed line) versus excitation energy for the Au source.
