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Formation and decay of hot nuclei in the $^{64}Zn + ^{nat}Ti$ and $^{36}Ar + ^{27}Al$ reactions at intermediate energies

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inferred for light particles and IMF's, whereas a smaller value of expansion is needed for the heaviest IMF's.

7. Conclusion

We studied the formation and de-excitation mechanisms of hot nuclei in $^{64}Zn+^{nat}Ti$ and $^{36}Ar+^{27}Al$ reactions at intermediate energies. Their mass and excitation energy of hot nuclei have been deduced from kinematical characteristics of their de-excitation products. The primary mass is slightly lower than the projectile mass, independent of impact parameter and bombarding energy, whereas the excitation energy per nucleon increases with the decrease of impact parameter and the increase of bombarding energy. Hot nuclei decay by an isotropic emission of LCP's and IMF's. In the most central collisions, excitation energies larger than 10 MeV per nucleon are reached. The data are well reproduced by a model simulating the statistical emission from a hot source in which some part of the total excitation energy is assigned to an isotropic collective expansion.

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FORMATION AND DECAY OF HOT NUCLEI IN THE ^{64}Zn + ^{nat}Ti AND ^{36}Ar + ^{27}Al REACTIONS AT INTERMEDIATE ENERGIES *

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ABSTRACT

The formation and de-excitation mechanisms of hot nuclei have been studied in the ^{64}Zn+^{nat}Ti and ^{36}Ar+^{27}Al reactions at intermediate energies. The mass and excitation energy of hot nuclei have been reconstructed from the kinematical characteristics of their decay products. In the most central collisions and for the highest bombarding energies, very high excitation energies, larger than 10 MeV per nucleon, are obtained. Comparison of the data with theoretical predictions show that a part of the excitation energy is associated with an isotropic collective expansion whose magnitude increases with the excitation energy.

1. Introduction

At present, one of the most debated issues in collisions of nuclei at intermediate energies is concerned with properties of hot and dense nuclear matter, and in particular the so-called multifragmentation process as well as the search for a liquid–gas phase transition. A scenario very often invoked is the occurrence of a compression–expansion phase at the beginning of the interaction between the projectile and target. After a rapid initial compression, the hot nuclear matter expands towards low density regions where it can break up into fragments [1,2]. From the fragment kinetic energies,

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we expect to gain information about the magnitude of radial flow resulting from the expansion phase. Indeed, some results become available in the litterature, going from a fraction of MeV per nucleon up to more than 10 MeV per nucleon [3,4,5].

In this contribution, we will report on the properties of hot nuclei formed in the ^{64}Zn+^{nat}Ti and ^{36}Ar+^{27}Al reactions at intermediate bombarding energies. Emphasis will be put on the careful sorting and reconstruction of hot nuclei as well as on their de-excitation modes.

2. Experimental procedure

The ^{64}Zn+^{nat}Ti reactions were measured at several bombarding energies between 35 and 79 MeV per nucleon and the ^{36}Ar+^{27}Al reactions between 55 and 95 MeV per nucleon. The experimental procedure can be found elsewhere [6,7]. Charged particles were detected in two plastic multidetectors [8,9] covering a total solid angle of 84% of 4π, between 3 and 150°. Identification of light charged particles (LCP's, Z=1 and 2) was achieved for energies above 2.5 MeV per nucleon. For intermediate mass fragments (IMF's, $3 \leq Z \leq 8$), their detection was achieved above 2.5–5 MeV per nucleon but their identification was possible only above 15–20 MeV per nucleon. Heavier fragments were detected and identified in an additional set of ΔE–E telescopes between 3 and 30°.

3. Event selection

When plotting the correlation between the total multiplicity of charged products detected in an event and the corresponding total parallel momentum, two distinct regions are evidenced [6]. Only the well characterized events with high values of multiplicity and parallel momentum have been considered in the subsequent analysis. They have a mean total detected charge of $\approx$ 70% of the total charge and a mean total parallel momentum $\approx$ 80% of the incident momentum [7].

To compare the data with theoretical predictions, the events were sorted as a function of the impact parameter b_{EXP} deduced from the total transverse momentum $P_\perp$ taken as the sum of transverse momentum moduli of all particles detected in an event. For that purpose it was assumed that the largest values of total transverse momentum are associated to the most central collisions [7]. When comparing the data and calculations the real impact parameter was disregarded. Instead, an "experimental" impact parameter b_{EXP} deduced from $P_\perp$ as for the experiment [10] was used.

4. Reconstruction of hot nuclei

The emission sources are recognized from invariant cross sections $d^2\sigma/V_\perp dV_\perp dV_\parallel$ plotted in the velocity plane. The cross sections have been drawn for LCP's and IMF's and for different impact parameters bin [7]. With Z=1 and 2, two sources come out : A fast source associated with the PLF and a slow one associated with the TLF. The slow source is not visible with IMF's due to experimental velocity thresholds. A third component centered at half the beam velocity is seen with Z=1 particles and to a lesser extent with Z=2 : It is attributed to a pre-equilibrium emission originating from nucleon–nucleon collisions in the early stage of the interaction. These features are observed at all energies for both systems and demonstrate that we are dealing with binary dissipative collisions accompanied by a pre-equilibrium emission, as already noted [11]. This statement is supported by results of theoretical predictions performed with the statistical EUGENE code [12] and dynamical QMD code [13] as well as by the disappearance of significant fusion-like cross section above 50 MeV per nucleon [14].

One way to access the nature of the initial hot nucleus (the fast source) is to determine its characteristics from those of all its decay products. An isotropic emission pattern of LCP's and IMF's from a decaying source emerges from invariant cross sections $d^2\sigma/V_\perp dV_\perp dV_\|$. A more precise evaluation is obtained by looking at the angular distributions of LCP's and IMF's in the rest frame of the hot nucleus. For that purpose the source velocity has been determined in two ways : Either the mean value of parallel velocity distribution of fragments with Z≥6 has been considered for each impact parameter [6,7], or the source velocity vector has been reconstructed for each event from momenta of all fragments with Z≥2 [15]. Both methods lead to similar results. Isotropic angular distributions of Z=2 and IMF's are evidenced in the forward hemisphere in the rest frame of the source, for the two systems whatever the impact parameter and bombarding energy are. Such a behaviour is not seen for Z=1 due to the pre-equilibrium emission and a bad identification of Z=1 below 10 degrees in the laboratory system [16]. However, it has been assumed that all particles emitted in the forward hemisphere in the hot nucleus frame originate from this hot nucleus. Consequently, its charge is build by adding to the heaviest detected fragment twice the charge of particles forward emitted in its frame and its mass was deduced from its charge using the A/Z ratio of the projectile.

For the ^{64}Zn+^{nat}Ti reactions, the mass of the heaviest detected fragment is shown in fig. 1 as a function of b_{EXP} for different bombarding energies. The strong decrease of the heaviest fragment mass with b_{EXP} reveals that more energy is deposited in the primary nucleus when going from peripheral to central collisions. In fig. 1 is also shown the reconstructed mass of the primary hot nucleus, corrected for the geometrical inefficiency. A nearly constant mass value slightly lower than that of the projectile is observed whatever b_{EXP} and bombarding energy are. This behaviour is an indication in favor of a binary reaction mechanism. However, the primary mass is overestimated since pre-equilibrium particles emitted in the forward hemisphere have been summed up. This component is responsible for the slight rise of the primary mass in central collisions. Relying upon statistical calculations [12], the mass overestimation is found to increase with the decrease of b_{EXP}, reaching 15% in the most central collisions [10]. Similar results are obtained in the ^{36}Ar+^{27}Al reactions [15].

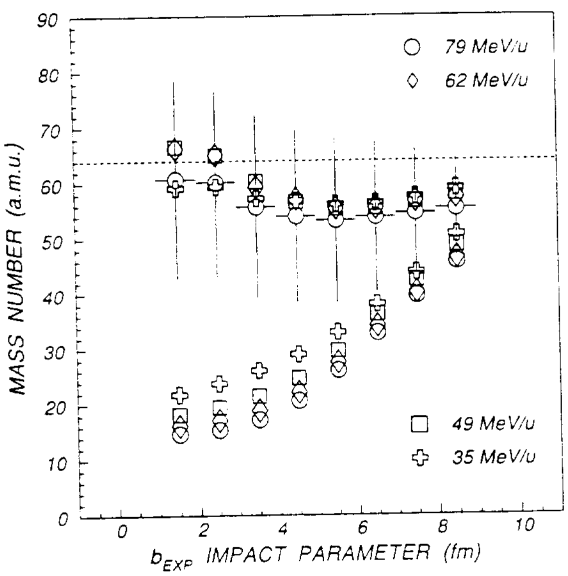

Fig. 1. Masses of the heaviest detected fragment (lower symbols) and primary hot nucleus (upper symbols) measured in the $^{64}Zn+^{nat}Ti$ reactions versus b_{EXP} and bombarding energy.

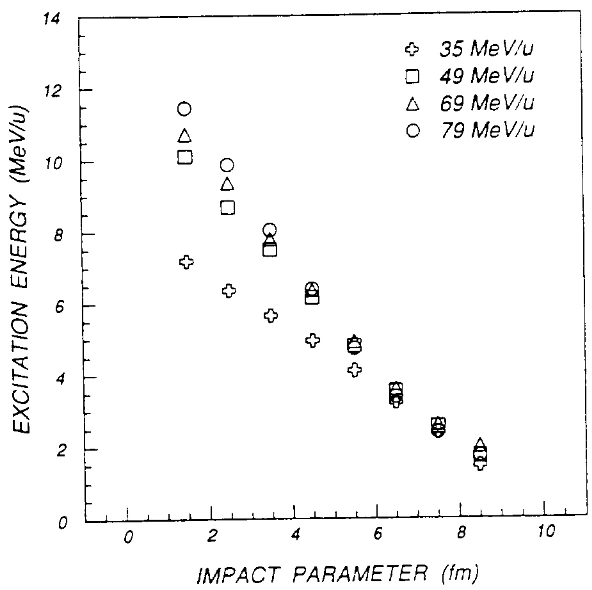

Fig. 2. Mean values of excitation energies of hot nuclei in the $^{64}Zn+^{nat}Ti$ reactions versus b_{EXP} and bombarding energy.

5. Excitation energy

Once the nature of the primary hot nucleus has been accessed, it is then possible to calculate its excitation energy from the kinetic energies of all its decay products [6]. The excitation energy distributions have been calculated on an event by event basis taking into account the neutrons contribution as well as the Q-value of the reaction. Excitation energies measured in the $^{64}Zn+^{nat}Ti$ at several bombarding energies are shown in fig. 2 as a function of b_{EXP}. As expected, for a given bombarding energy, the excitation energy increases with the decrease of b_{EXP}, starting from less than 2 MeV per nucleon in semi-peripheral collisions. In central collisions, the excitation energy increases with the bombarding energy, reaching 11–12 MeV per nucleon at 79 MeV per nucleon. In fig. 3 are shown the results obtained in the analysis of the $^{36}Ar+^{27}Al$ reactions. Similar trends are observed with maximum excitation energies of 9–11 MeV per nucleon. As for the mass determination, the data shown in figs. 2 et 3 are upper limits due to the pre-equilibrium component. Simulations [12] lead to an overestimation of the excitation energy of $\approx 15\%$ in the most central collisions [10]. Nevertheless, taking into account for this correction, the data show that very excited nuclei are formed with excitation energies larger than 10 MeV per nucleon.

In order to give an insight into the formation and decay mechanisms of hot nuclei.

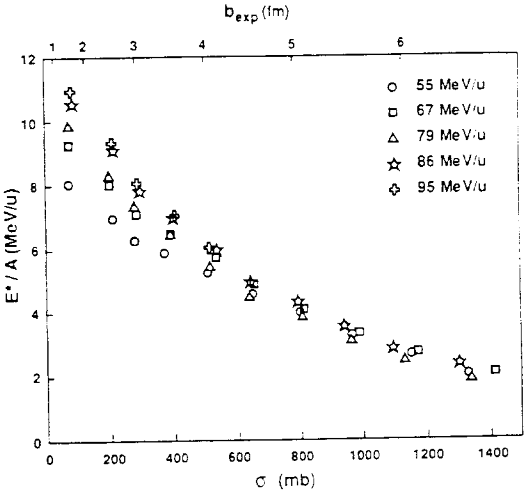

Fig. 3. Mean values of excitation energies of hot nuclei in the $^{36}Ar+^{27}Al$ reactions versus b_{EXP} and bombarding energy.

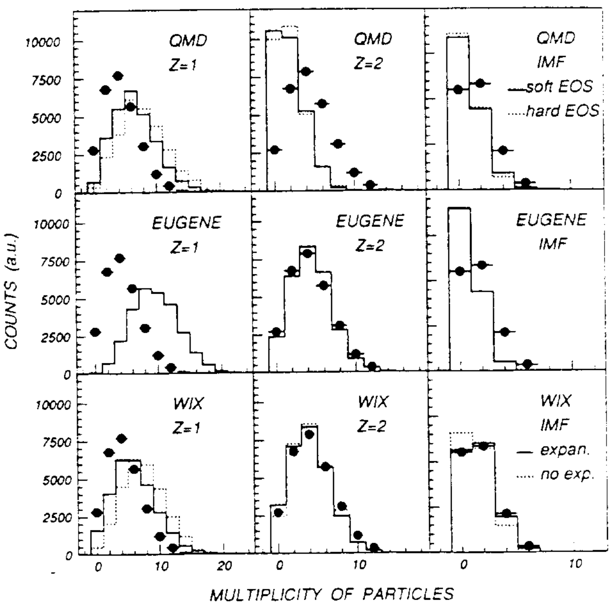

Fig. 4. Multiplicity distributions of Z=1, Z=2 and $3 \leq Z \leq 8$ emitted by hot nuclei in the 79 MeV per nucleon $^{64}Zn+^{nat}Ti$ reactions, compared to theoretical predictions : QMD [13], EUGENE [12] and WIX [17].

calculations have been carried out and compared to the data : The statistical EUGENE code [12] and dynamical QMD code [13] which both follow the entire evolution of the collision and the statistical WIX code [17] which simulates multifragmentation of one single source. Experimental excitation energy distributions have been compared to predictions of EUGENE and QMD codes at 79 MeV per nucleon [10]. As mentioned before, the calculated events have been filtered by the acceptance of the experimental setup and analyzed in the same way as the data. An excellent agreement between the data and QMD calculations is ascertained, while EUGENE overpredicts excitation energies by 2 MeV per nucleon in central collisions.

6. Multiplicities and kinetic energies

Now we will concentrate on the multiplicity distributions of particles emitted by hot nuclei as well as on their kinetic energy spectra. Only the most central collisions ($b_{EXP} \leq 2$ fm) measured in the 79 per nucleon $^{64}Zn+^{nat}Ti$ reactions, corresponding to a measured cross section of 125 mb and to an excitation energy of 11–12 MeV per nucleon, are concerned in the subsequent analysis. In fig. 4 experimental multiplicities of Z=1, Z=2 and $3 \leq Z \leq 8$ are compared to various predictions. The QMD calculations (using a soft or a hard equation of state) overpredict the yield of Z=1 while giving a two low number of Z=2 and IMF's. The EUGENE calculations overestimate the

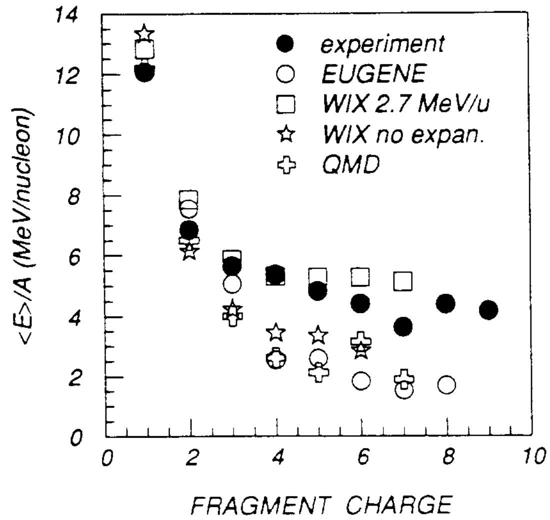

Fig. 5. Mean values of kinetic energy spectra as a function of fragment charge for the 79 MeV per nucleon $^{64}Zn+^{nat}Ti$ reactions, compared to theoretical predictions : QMD [13], EUGENE [12] and WIX [17].

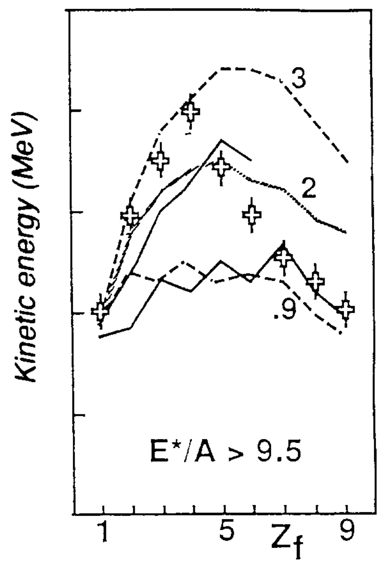

Fig. 6. Mean values of kinetic energy spectra as a function of fragment charge for $^{36}Ar+^{27}Al$ reactions, compared to theoretical predictions : EUGENE (dashed lines) [12] and WIX (solid lines) [17].

yield of hydrogen nuclei by more than a factor of 2, gives the right number of Z=2 and underpredicts the number of IMF's. On the other hand, an overall agreement is obtained with the WIX calculations assuming an isotropic collective expansion of 2.7 MeV per nucleon. The switching off of collective expansion changes the results in a more abundant emission of Z=1 since more thermal energy is available [17].

In fig. 5 is displayed the mean kinetic energy per nucleon of LCP's and IMF's as a function of their atomic number. A flat behaviour of the kinetic energy comes out for IMF's, as already observed [3]. All models fail at reproducing the data : The IMF's energies are underestimated by more than 2 MeV per nucleon. Indeed, the WIX calculations alone reproduce in a quantitative way the experimental data. Detailed comparisons with the data [10] point out a value of isotropic radial flow in betwen 2 and 2.5 MeV per nucleon. Furthermore, no significant evolution of the fragment kinetic energy as a function of the atomic number is observed at variance with ref. [5].

In fig. 6 similar data are presented for the $^{36}Ar+^{27}Al$ reactions and hot nuclei with an excitation energy larger than 9.5 MeV per nucleon. In refs. [10,15], it has been shown that statistical sequential calculations account for the data up to excitation energies of 5–6 MeV per nucleon. Above this value, an increasing collective expansion energy is needed to describe the experiment. Statistical predictions of EUGENE and WIX with incorporation of a radial flow of 2 MeV per nucleon compare qualitatively well with the data. However, from fig. 6 a higher value of collective expansion can be