Properties of Very Hot Nuclei Formed in ^{64}Zn + ^{nat}Ti Collisions at Intermediate Energies

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Formation and decay of hot nuclei have been studied in ^{64}Zn + ^{nat}Ti collisions between 35 and 79 MeV/nucleon. The mass and excitation energy of excited quasiprojectiles are reconstructed from the kinematical characteristics of their decay products. In central collisions, excitation energies larger than 10 MeV/nucleon are reached. Comparisons with theoretical predictions indicate that a fraction of the excitation energy is associated with an isotropic radial flow. [S0031-9007(96)00539-X]

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One of the presently most debated questions in heavy-ion physics at intermediate energies focuses on the properties of hot nuclear matter and, in particular, on the so-called multifragmentation process as well as on the search for a liquid-gas phase transition. A very often invoked scenario is the occurrence of a compression-expansion phase at the beginning of the interaction between projectile and target. In the course of such a process, after an initial compression, the hot nuclear matter expands towards low density regions where it can break up into fragments [1–4]. An alternative to this scenario is the occurrence of an expansion just arising from the pressure induced by the thermal energy [5]. From the fragment kinetic energies, we expect to gain information about the magnitude of the collective radial flow resulting from the expansion phase. Indeed, recent results show evidence for a collective energy of a few MeV/nucleon at bombarding energies lower than 100 MeV/nucleon [6–11], and reaching even higher values (>10 MeV/nucleon) at higher bombarding energies [11–15].

This Letter reports on the properties of hot nuclei formed in the ^{64}Zn + ^{nat}Ti reaction, which was investigated at GANIL at several bombarding energies between 35 and 79 MeV/nucleon [16]. Light charged particles (LCP's: $Z = 1$ and 2) and intermediate mass fragments (IMF's: $Z \geq 3$) were detected in two plastic multidetectors covering a total solid angle of 84% of 4π, between 3° and 150° [17,18]. Detection of LCP's and IMF's was achieved for energies above 2.5 MeV/nucleon. Identification of IMF's was possible only above 15–20 MeV/nucleon. Heavier fragments were detected and identified in an additional set of seven ΔE-E telescopes between 3° and 30°.

The events were sorted according to the violence of the collision measured by the total transverse momentum, taken as the sum of the moduli of transverse momenta of all particles detected in an event. It was assumed that the transverse momentum is maximum for head-on collisions and is a decreasing function of the impact parameter. The experimental impact parameter $b_{\rm exp}$ has been derived from the measured differential cross section [16]. Results of simulations exhibit a linear relationship between $b_{\rm exp}$ and the true impact parameter with a standard deviation of 1–1.5 fm [19].

The correlation between the total multiplicity of charged products detected in an event and the corresponding total parallel momentum displays two distinct regions [16]. Low values of multiplicity and parallel momentum are associated with peripheral collisions in which both the projectilelike and targetlike fragments were not detected, while high values of multiplicity and parallel momentum correspond to well-characterized events: on average 70% of the total charge and 80% of the incident momentum were collected. Only these well-characterized events are considered in the subsequent analysis.

From the invariant cross sections of LCP's plotted in the velocity plane, two sources are extracted: a fast source associated with the quasiprojectile and a slow one associated with the quasitarget. A third component centered at half the beam velocity appears essentially with $Z = 1$ and to a lesser extent with $Z = 2$ [19]. This midrapidity emission has been interpreted as a pre-equilibrium emission originating at the beginning of the interaction between projectile and target. These features are observed at all energies and all impact parameters. They suggest binary dissipative collisions accompanied by pre-equilibrium emission [20]. This statement is

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reinforced by the disappearance of significant fusionlike cross section above 50 MeV/nucleon [19], as well as by the results of theoretical predictions performed with the statistical model EUGENE [21] and the quantum molecular dynamical code QMD [22].

In the following, we will concentrate on the properties of the fast source, the reconstructed quasiprojectile (QP), since most its decay products are well detected by the experimental setup due to their high velocities. On the average, 85% of the QP charge was detected (geometrical efficiency). The source velocity has been calculated from the momenta of all products having velocities larger than the center of mass velocity. In the forward hemisphere of the QP frame, the angular distributions of LCP's and IMF's display an isotropic emission, whatever the impact parameter and bombarding energy [19,23]. On the other hand, in the backward hemisphere, anisotropic angular distributions are observed due to the influence of midrapidity pre-equilibrium particles and particles coming from the quasitarget. In order to get rid of these nonisotropic components, the QP charge was constructed by adding to the charge of the largest detected fragment (QP residue) twice the sum of the charges of the forward emitted particles. The sum has been corrected for the geometrical inefficiency: In central collisions at 79 MeV/nucleon, two charge units on average are lost down the beam pipe. The QP mass was deduced from its charge using the A/Z ratio of the projectile.

The mass of the largest detected fragment, shown in Fig. 1(a), strongly decreases when $b_{\rm exp}$ decreases revealing that more energy is deposited in the reconstructed QP when going from peripheral to central collisions. For a given $b_{\rm exp}$, the mass decreases when the bombarding energy increases, indicating that the energy deposit goes up with the bombarding energy. The reconstructed QP mass is shown in Fig. 1(b). Since the mass is built from all charged particles emitted in its forward hemisphere and since some pre-equilibrium contribution is included in those forward emitted particles, the reconstructed mass is overestimated compared to the actual one. Relying upon calculations performed with the code EUGENE, the mass overestimate was found to be $\approx 15\%$ in central collisions. Accounting for this fact, a nearly constant mass value slightly lower than the projectile mass would be observed as a function of $b_{\rm exp}$ and bombarding energy. This behavior is an additional indication in favor of a binary reaction mechanism. Similar results were obtained in the ^{36}Ar + ^{27}Al reaction [24].

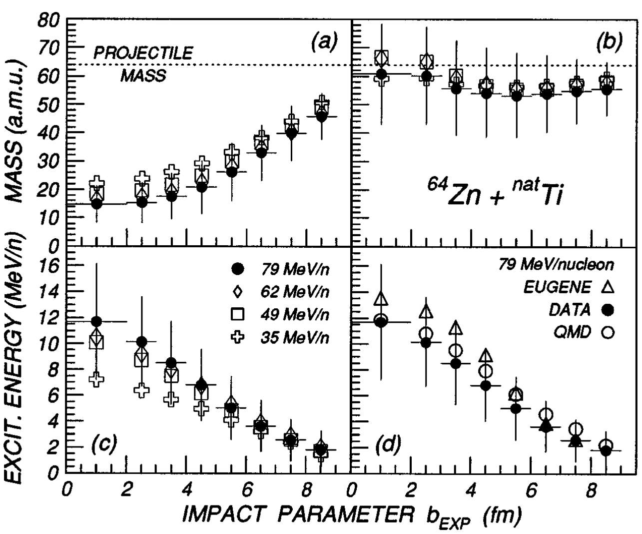

FIG. 1. Average values of the largest detected fragment in panel (a), of the reconstructed mass of the quasiprojectile in panel (b), and of the excitation energy of the quasiprojectile in panel (c), as a function of the reconstructed impact parameter $b_{\rm exp}$. In panel (d) the excitation energy measured at 79 MeV/nucleon is compared to predictions of the statistical model EUGENE [21] and QMD [22]. The vertical bars account for standard deviations.

The QP excitation energy can be determined from the kinetic energies of all its decay products [16,25]. It has been calculated event by event taking into account the contribution of the neutrons as well as the Q value of the reaction. The average excitation energy is shown in Fig. 1(c) as a function of $b_{\rm exp}$. As expected, for a given bombarding energy the excitation energy increases when $b_{\rm exp}$ decreases, starting from less than 2 MeV/nucleon in peripheral collisions. The excitation energy increases with the bombarding energy, reaching 11–12 MeV/nucleon in central collisions at 79 MeV/nucleon. Because of the contribution of pre-equilibrium particles, the average excitation energies shown in Fig. 1(c) are upper limits. For central collisions at 79 MeV/nucleon, EUGENE simulations lead to a fast pre-equilibrium component of five charge units carrying away (25–30)% of the total excitation of the reconstructed QP, thus reducing the excitation energy per nucleon of the true QP (after subtraction of pre-equilibrium particles) by $\approx 15\%$. Relying upon this calculation, an average value of 10 MeV/nucleon is inferred from the data. Because of the method of reconstruction the fluctuations of excitation energy are broad. Nevertheless, a significant fraction of QP's bear excitation energy in excess of 10 MeV/nucleon.

In order to give an insight into the formation and decay mechanisms of these very hot nuclei, calculations have been carried out and compared to the data. The calculated events have been filtered by the acceptance of the experimental setup and analyzed in the same way as the data. In Fig. 1(d) the excitation energy measured at 79 MeV/nucleon is compared to EUGENE [21] and QMD [22] calculations aiming at reproducing the complete evolution of the collision. An excellent agreement between the data and QMD calculations is ascertained, while the EUGENE code overpredicts the excitation energy by 2 MeV/nucleon at low $b_{\rm exp}$.

Hereafter, we will concentrate on central collisions measured at 79 MeV/nucleon with $b_{\rm exp} \leq 2$ fm. Experimental multiplicities of LCP's and IMF's are compared to theoretical calculations in Fig. 2. The QMD calculations overpredict the yield of $Z = 1$ and underpredict the number of $Z = 2$ and IMF's. The EUGENE calculations overestimate the yield of $Z = 1$ by more than a factor of 2, give the right number of $Z = 2$, and underpredict the number of IMF's. The data are also compared with predictions performed with the statistical code WIX [26], an improved version of the earlier FREESCO code [27]: The Coulomb interaction between the excited prefragments is introduced and a collective radial flow can be injected. As a consequence, less thermal energy is left for the decay process and more IMF's are produced. The calculations were carried out assuming a single nucleus of ^{59}Co, with an excitation energy of 12 MeV/nucleon and a freeze-out density of $\rho/\rho_0 \approx 1/3$. As seen in Fig. 2, the description of the data is improved when a part of the excitation energy is stored in an isotropic collective expansion. The switching off of the collective expansion changes the results in a more abundant emission of $Z = 1$ since more thermal energy is available [26].

The elemental charge distribution for central events is compared to simulations in Fig. 3. The QMD calculation overpredicts the yield of $Z = 1$ and gives a too low number of $Z = 2$ and IMF's. As a result, an excess of high atomic number products is observed. A too great yield of $Z = 1$ is also predicted by EUGENE, leading to a deficiency of both IMF's and heavier fragments. A slight improvement is obtained with the WIX calculation, although the yield of $8 \leq Z \leq 12$ is underestimated by 1 order of magnitude.

The kinetic energy of fragments is displayed in Fig. 4. No data appear for $Z \geq 10$ since these nuclei are poorly identified in charge due to limitations of the experimental setup. A flat behavior of the kinetic energy is evident for $Z \geq 3$. Results of simulations have been plotted for fragments with $Z \leq 8$. The too low calculated yields for heavier fragments prevent us from getting meaningful predictions. All models which do not incorporate a radial flow underestimate the energy of $Z \geq 3$ by more than 2 MeV/nucleon. The WIX calculations with incorporation of an isotropic radial flow reproduce the data in a qualitative way. The extracted value of the radial flow is in between 1.8 and 2.7 MeV/nucleon, corresponding to a fraction of (10–15)% of the total available kinetic energy. No significant evolution of the radial flow is observed as a function of the atomic number.

This result can be compared to previous results obtained in nucleus-nucleus collisions below 100 MeV/nucleon. A radial flow of 3.5 MeV/nucleon was deduced from the analysis of the S + Al reaction [10]. No effect was seen in the closely related Ca + Ca system [28]. A value of 1 to 2.5 MeV/nucleon was deduced from the ^{36}Ar + ^{27}Al reaction [29] and 3 MeV/nucleon were measured in emulsion experiments

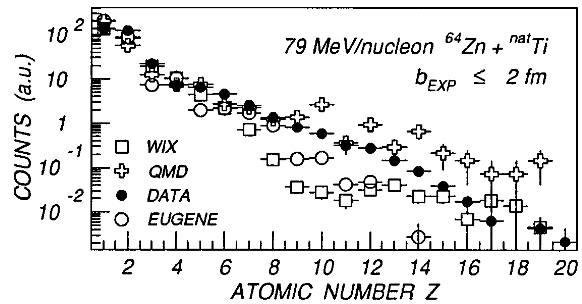

FIG. 3. Elemental charge distribution of quasiprojectile products is compared to the predictions of QMD [22] and statistical models EUGENE [21] and WIX [26].

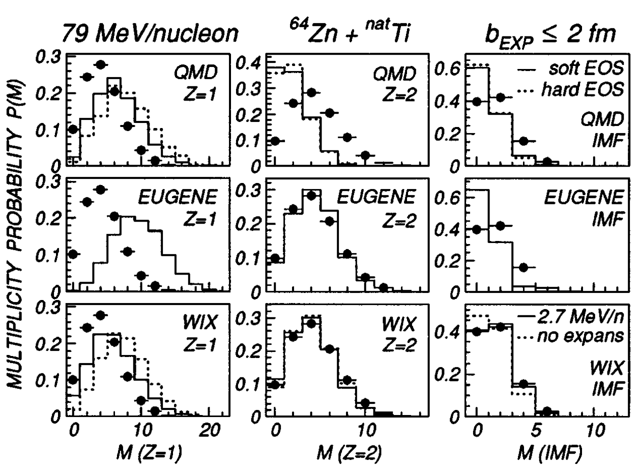

FIG. 2. The experimental multiplicity distributions of $Z = 1$, $Z = 2$, and IMF's are compared to the predictions of QMD [22] and statistical models EUGENE [21] and WIX [26].

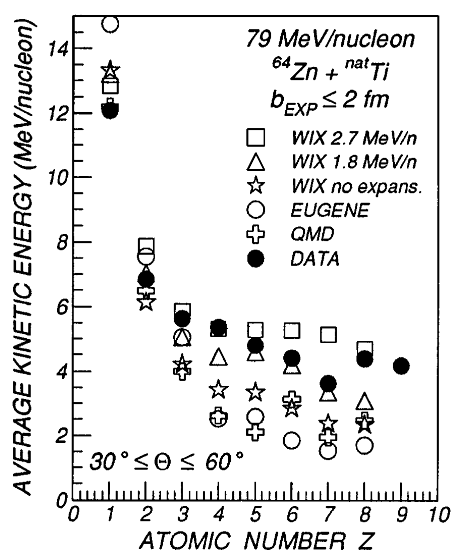

FIG. 4. Mean kinetic energy of fragments, emitted in the frame of the quasiprojectile at $30° \leq \Theta \leq 60°$, is compared to the predictions of QMD [22] and statistical models EUGENE [21] and WIX [26].

[6,11]. The analysis performed on the 50 MeV/nucleon Xe + Au reaction [7] gives support for a radial energy of the heavy residue of 1.5–2 MeV/nucleon, in agreement with the value of 2 MeV/nucleon extracted from the study of the 50 MeV/nucleon Xe + Sn reaction [30].

From the above detailed comparisons, it is demonstrated that the statistical WIX model reproduces the charge, multiplicity, and kinetic energy distributions of IMF's, as well as their kinetic energy spectra [19]. As already mentioned, the compressional energy is much more efficient than thermal energy to disintegrate a nucleus [5,31]. As a result, the IMF multiplicity is strongly enhanced. In view of the success of the description of the data by the WIX code, it is tempting to conclude that the hot nuclei have reached a statistical equilibrium. Nevertheless, further dynamical calculations have to be carried out before deciding about the validity of such a global thermodynamical concept.

To summarize, formation and decay of excited quasiprojectiles produced in the ^{64}Zn + ^{nat}Ti reaction have been studied at intermediate energies. The mass and excitation energy of quasiprojectiles were determined from the kinematical characteristics of their decay products. In central collisions, excitation energies larger than 10 MeV/nucleon are reached. The data are satisfactorily reproduced by a statistical decay of a hot source, in which 2.3 $\pm$ 0.5 MeV/nucleon are stored into an isotropic radial flow. The following scenario may be invoked: The hot nucleus expands and emits isotropically LCP's and IMF's while boosting their radial velocities. However, the origin of this expansion is not still cleared up since both a compression-expansion cycle and a thermally induced pressure can account for this collective effect.

This experiment was performed at GANIL, Caen, France.

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