FORMATION OF HOT NUCLEI IN COLLISIONS BELOW 100 MeV/u AND THE CALORIC CURVE* **

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4π charged products arrays allowed us to determine that, at incident energies 35–95 MeV/u, the fusion cross section is very small in nearly symmetric light and medium systems. Dissipative binary collisions accompanied by mid-rapidity (participant) emission was found to dominate at all impact parameters. The excitation energy of the reconstructed quasi-projectile was obtained via calorimetry and reaches high values. Their apparent temperatures were obtained from several double isotopic yield ratios and slopes of kinetic energy spectra. These data can be explained by a steady increase of the initial temperature with excitation energy without evidence for a liquid–gas phase transition.

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1. Introduction

In order to study hot nuclei formed in nucleus–nucleus collisions, one must first determine the number of hot nuclei formed. This number varies with the incident energy and impact parameter. Below $\approx$ 15 MeV/u, complete fusion cover a broad range of impact parameters and deep inelastic collisions are observed to semi-peripheral collisions. Above 200 MeV/u, a participant zone is formed at all impact parameters. In very central collisions, it contains all nuclei (full stopping events) but is otherwise accompanied by two "spectators".

At energies in the range 25–100 MeV/u, inclusive experiments and experiments performed with 4π arrays having a rather large detection threshold were analysed assuming implicitly or explicitly that fusion — one main source events — dominated. Contradictory results were obtained for the

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** Experiments performed at GANIL.

temperature and excitation energy of these nuclei. The construction of low threshold and high geometrical efficiency allowed us to reach very different conclusions and to undertake detailed studies of the temperature and excitation energy of nuclei whose almost all decay products were detected.

2. Dominance of dissipative binary processes

A first series of measurements was made with the 4π array Mur + Tonneau at GANIL. Nearly symmetric systems ^{35}Ar + ^{27}Al, ^{64} Zn + ^{58} Ni and ^{64} Zn + ^{48}Ti were studied [1, 2] between 35 and 95 MeV/u. Two global variables were used for impact parameter sorting of well-characterized events. A shape analysis of central collisions showed that less than 3% of σ_R can be attributed to events with one main source. All other events exhibit three sources. A mid-rapidity source, emitting essentially light particles ($Z = 1, 2$) for these light systems, corresponds to emission from the interaction zone (participants). The main parts of the projectile and target nuclei form a quasi-projectile (QP) and a quasi-target similar to deep inelastic collisions at low incident energies. Since all products from the QP are well above the detection threshold, one can reconstruct it in each event and determine its velocity, charge and mass, and excitation energy. The correlation between its kinetic energy per nucleon and deflection angle is the usual "Wilczynski plot", but full damping of the initial relative motion is not, or rarely, reached.

The QP mass is close to the projectile mass and decreases at low impact parameter values. Its excitation energy was calculated via calorimetry: the kinetic energies of its products in its reference frame were added to the mass balance. Large values are reached in central collisions. These products are emitted isotropically in the QP frame, indicating thermalization could have occurred.

Fig. 1 displays schematically the evolution of reactions with energy. In very central collisions the whole relative motion is transformed into other degrees of freedom: fusion at low energy, full stopping at high energies. For less central collisions, fusion still occurs at low energy; when deep inelastic collisions replace fusion the relative motion is fully damped and the total excitation energy of the QP and QT is close to the available energy. Around the Fermi energy, complete damping does no longer occur, the QP and QT carry a lower proportion of the available energy (but a larger absolute value) as excitation energy. Mid-rapidity emission sets in (also called pre-equilibrium emission or participants) and becomes increasingly important.

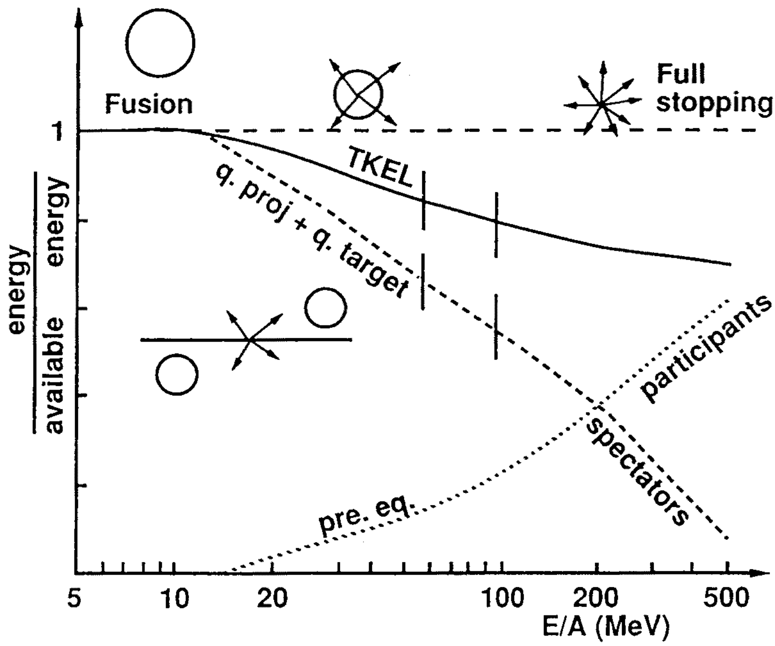

Fig. 1. Schematic picture of the evolution of reaction mechanisms with incident energy. Long dashed line : single source events (fusion or full stopping) in the most central collisions ($< 1\% \ \sigma_R$). Other lines : central collisions ($< 4\% \ \sigma_R$). Solid line: Total Kinetic Energy Loss TKEL (dissipated energy). Dotted line: total energy carried by mid-rapidity particles (pre-equilibrium or participants). Short dashed line : E^* of the quasi-projectile + quasi-target, or spectators. From [1].

3. Caloric curve

The broad range of excitation energies E^* of QP's at a single incident energy makes it possible to study the correlation between the temperature T and E^* as in [3], where a liquid-gas phase transition was observed. The advantage here is that nearly constant QP masses could be selected. This analysis was made on data obtained with the 4π array INDRA. The temperatures measured are not the initial ones, but apparent temperatures averaged over the de-excitation of the primary nucleus and emitted fragments. Two sets were obtained [4]:

— $T\mathrm{r}^0$ values calculated from the measured yields of several pairs of isotopes differing by one neutron. In Fig. 2 left are shown $T\mathrm{r}^0$ values obtained with pairs having a good sensitivity (binding energy differences $\geq$13 MeV). The three $T\mathrm{r}^0$ values differ, confirming that these

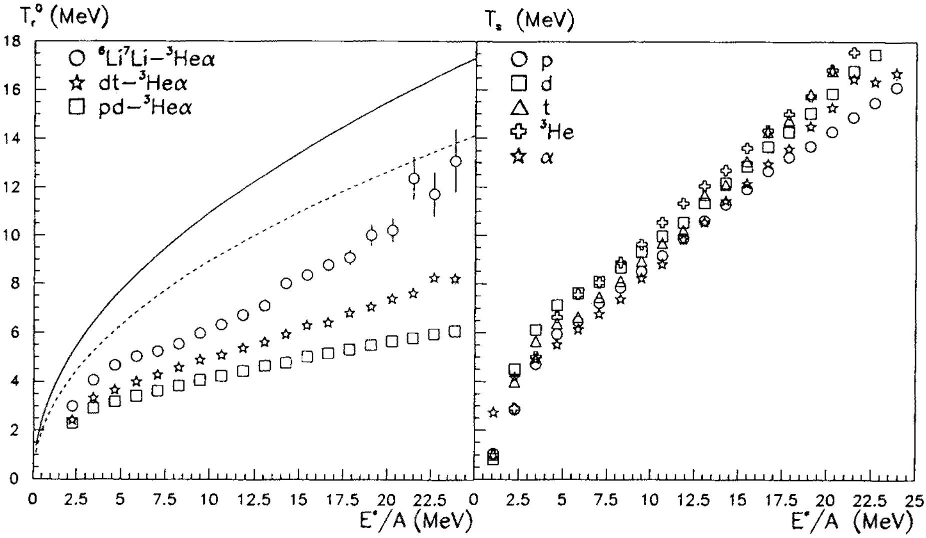

Fig. 2. Measured apparent temperatures versus excitation energy per nucleon of the quasi-projectile formed is ^{36} Ar + ^{58}Ni collisions at 95 MeV/u. Left panel: Tr^0 from double isotopic yield ratios. For orientation, the Fermi gas relation is shown with A/12(thick line) and A/8 (dashed line). Right panel: Slope parameters from kinetic energy spectra. From [4].

apparent temperatures cannot be used directly as a measure of the initial temperature. No plateau is observed, at variance with Aladdin data [3]

— Slope parameters Ts obtained with the usual fits on kinetic energy spectra of light particles: Fig. 2 right. They are also apparent temperatures, averaged over the de-excitation chain and affected by successive recoil effects. They agree together within ±10%, increase rapidity with E^*/A and are larger than Tr^0 values.

If the QP's were thermalized, the various apparent temperatures must be reproduced with the same initial temperature $T_{\rm ini}$ in calculations including the population of all excited states contributing to the reduction or the feeding of the isotopes of interest. Two statistical models were used: sequential decay, mostly valid at low excitation energies, and simultaneous decay (multifragmentation) more likely at high E^*/A. The first calculation will be presented by Siwek at this meeting [5]. The other one is described in [4]. Both lead to the same conclusion : the data can be explained by a steady increase of $T_{\rm ini}$ with E^*/A, without assuming a plateau followed by a rise (first order liquid–gas phase transition). Up to $\approx$ 10 MeV/nucleon, the relationship between $T_{\rm ini}$ and E^*/A is very close to that of a Fermi gas and sequential statistical decay can explain the data. At higher E^*/A, multifragmentation sets in and a gradual increases of $T_{\rm ini}$ with E^*/A occurs.

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