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ONSET OF VAPORIZATION FOR THE Ar+Ni SYSTEM[1]

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Abstract

Using the 4π multidetector INDRA, collisions between ^{36}Ar and ^{58}Ni have been investigated over a broad bombarding energy range, from 32 to 95 AMeV. The onset for complete vaporization of the system into neutrons, H and He isotopes as well as the evolution with energy of the isotopic composition of the vaporization events were determined. Initial excitation energy needed for vaporization is discussed.

To improve our knowledge of the properties of nuclear matter under peculiar conditions of temperature and pressure, it is important in studying central nucleus-nucleus collisions at intermediate energies, to determine how and at which excitation energy the highly excited nuclear system formed disassembles. At a high enough energy, the multifragmentation process is predicted to set in, from both statistical and dynamical calculations[1]; even if the mechanisms involved are not yet fully understood, experimental evidences concerning the appearance of multifragmentation are now well established[1]. A second

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[1] Experiment performed at GANIL

interesting feature is expected to occur: the vaporization of the system[2, 3, 4, 5]. In the extreme only light particles ($Z \leq 2$) are produced, forming a gas phase as defined in ref[2]. However, the link between this vaporization process and the liquid-gas phase transition in infinite nuclear matter is not obvious and is much debated due to finite size effects and to the Coulomb force[6, 7]. Thus an experimental determination of the onset of vaporization should provide valuable information on the disassembly of hot nuclei.

The experimental investigation of vaporization events, which are here defined as events containing only light particles[8], needs devices capable of performing complete or quasi complete exclusive experiments. In an ideal experiment, an event by event detection of all the particles and fragments with their size (charge and mass), their spatial distribution and their energy should be obtained, thus permitting the exclusion of events containing fragments. Such an ideal experiment has been partially realized using the new 4π detector INDRA[9]. The basic detection modules of this detector comprise two (ionization chamber-CsI) or three (ionization chamber-silicon detector-CsI) stage telescopes, depending on detection angle, for complete identification of charged products on a large energy range.

A $193\mu g/cm^2$ ^{58}Ni target was bombarded by different energy ^{36}Ar beams: 32, 40, 52, 63, 74, 84 and 95 AMeV. The 95 AMeV beam was delivered directly by the accelerator whereas other energies were obtained by slowing down this beam, further analyzed by the "alpha magnetic spectrometer" of GANIL. Typical beam intensities were $3-4*10^7$ pps. For this first experiment the backward ionization chamber array of INDRA was not installed, preventing the separation between fragments and low energy (below 12 MeV) He isotopes at angles larger than 90°. A minimum bias trigger was chosen, namely a multiplicity value: events were registered when at least 3(4) modules fired for the incident energies 32-74 (84-95)AMeV. For absolute normalization purposes, some data were taken at 52 AMeV bombarding energy without any bias. Thus we could verify that the total measured cross-section agrees within 10% with the value predicted by the systematics on total reaction cross-sections established by Kox et al[10].

Only data concerned with the numbering of the identified charged products will be presented in this letter. The identification includes tests for the consistency of the responses of all detection layers passed through by a particle. In some cases this procedure allows to separate particles piled-up in one module; typically one can separate a fast light charged particle fully identified in a CsI scintillator from any slow particle stopped in the preceding silicon detector. An example of the results obtained is shown in fig.1(a). It represents the total detected charge (Z_{tot}, sum of the charges of all identified particles) versus the multiplicity of charged products. The remarkable feature is the quality of the detection: there are quite a number of events for which a large fraction of the total charge of the system (Z=46) is detected. Moreover this efficient detection covers a large range of multiplicity, from about 10 up to 35. Only a few events (0.02%) are found with Z_{tot} larger than 46. They correspond mainly to events in which the Z of a particle has been badly reconstructed when two particles piled up in one module.

Let us now examine events which were defined as vaporization events, without any

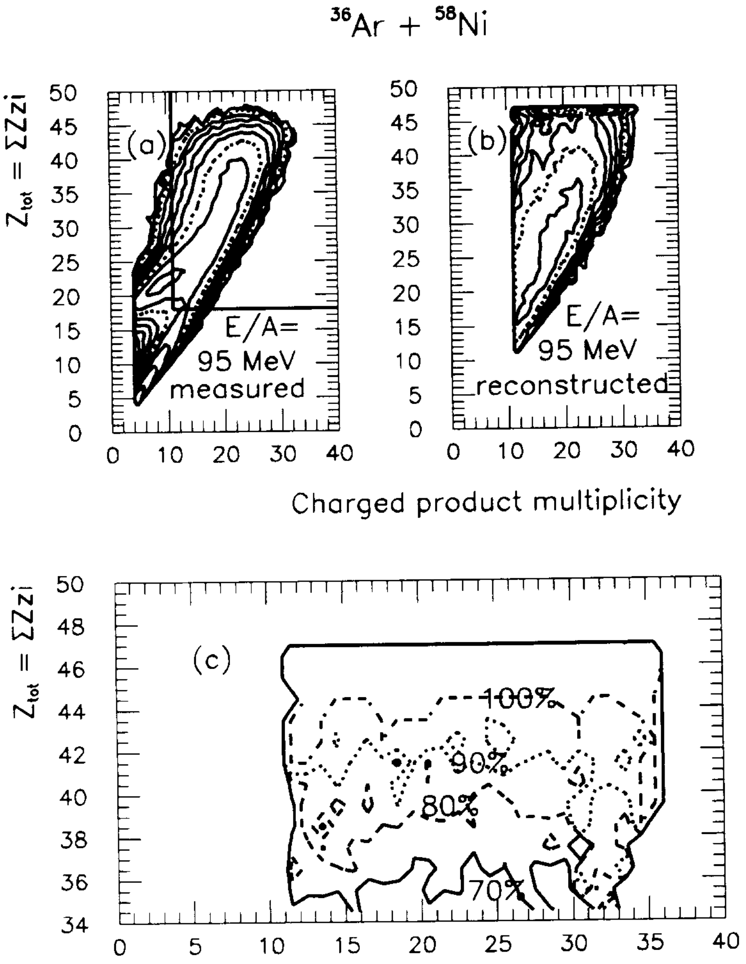

Figure 1: (a) Measured relation between charged product multiplicity and total detected charge. The total charge of the system is $Z_{tot} = 46$. The limits used in the simulated construction of events are indicated by the vertical and horizontal lines. (b) Same as (a), but for the reconstructed events obtained from the simulation (see text). Eleven contour levels (2^1 to 2^{11} events) are drawn in (a) and (b). (c) Contours for equal probabilities that no IMF has been lost.

assumption on the production mechanisms; as mentioned earlier these events contain only light charged particles. The safest way to correctly select such events would be to search them in the class of events where the detected charge Z_{tot} is greater than 44 (accepting that only one helium nucleus may be missing). In this case, the detection efficiency, ε, is very low and strongly depends on the particle multiplicity M (ε ~19% for M = 23 and ε ~1.7% for M = 46). Therefore we have enlarged the selection by decreasing the limit on Z_{tot} to accept events for which the probability to have detected all fragments is greater than 90%. This limit was determined with the help of a simulation[11]keeping only events with multiplicities larger than 10, which excludes events from peripheral collisions (fig.1(a)). Using the experimental Z distributions for different multiplicity bins, we assume that the true charge distributions are similar to the measured ones. Then, we construct complete events (Z_{tot}=46) by random sampling on the Z distributions. This gives calculated multiplicities; we go back to the measured multiplicities by discarding the appropriate number of nuclei. The reconstructed map Z_{tot} versus multiplicity, very similar to the measured one, is shown in fig. 1(b). We thus search for events for which the probability that a fragment ($Z > 2$) may have escaped detection is less than 10%. This criterion determines a limit on the total detected charge Z_{tot} which is found equal to 41 whatever the multiplicity and the incident energy (fig.1(c)). Finally the vaporization events are now defined as those for which Z_{tot} amounts at least to 41, and which contain no fragment. They are evidently located in the highest multiplicity region (multiplicity values in the range 25-35). With those conditions, the detection efficiency for vaporization events now amounts to ε ~0.4-0.5 almost independently of the particle multiplicity. It was verified that these rare events do not result from pile-up of events in one or several beam bursts. From the beam intensity (~ 3 particles/burst) and the vaporization event counting rate, the probability that such events result from the pile-up of two reactions in the same burst is estimated to be less than 10^{-4}. Secondly, only one peak associated with these events was observed in the time spectra[9]. And finally no vaporization events with Z_{tot} larger than 46 were observed.

The excitation function for vaporization, not corrected for detection efficiency, is shown in the left part of fig.2. The cross-section becomes sizeable above 52 AMeV and rises sharply to reach some 10^{-4} of the total reaction cross-section at 95 AMeV. It can therefore be inferred that, for this system, the onset for vaporization is around 50 AMeV which corresponds to 12 MeV available energy per nucleon in the total system.

For these vaporization events, the average measured particle multiplicities (M_{meas}), as well as the average multiplicities of each isotope, are reported in fig.2 (right part) as a function of bombarding energy. The most abundant particles are alpha particles: their relative yield decreases from 0.5 to 0.4 when the incident energy increases. While the relative proton yield remains nearly constant around 0.3, between 52 and 95 AMeV, the decreasing proportion of alpha particles is replaced by loosely bound isotopes, dominated by deuterons. Each of the measured events being completed in charge by particles (M_{cor} in fig.2) according to the measured yields, neutron multiplicities are deduced from atomic mass conservation and found very close to proton multiplicities (fig.2). Various explanations can be invoked to account for the strikingly large yield of alpha particles. The most simple concerns the symmetry of the total system (N~Z) which can favour the emission of alpha particles. A second explanation can be found if alpha particles are partly regarded as deexcitation products of low Z primary excited fragments. These two mechanisms of α production would be favoured if a sequential decay process occurs. More speculatively, the abundance of alpha particles can result from a property of nuclear matter which is

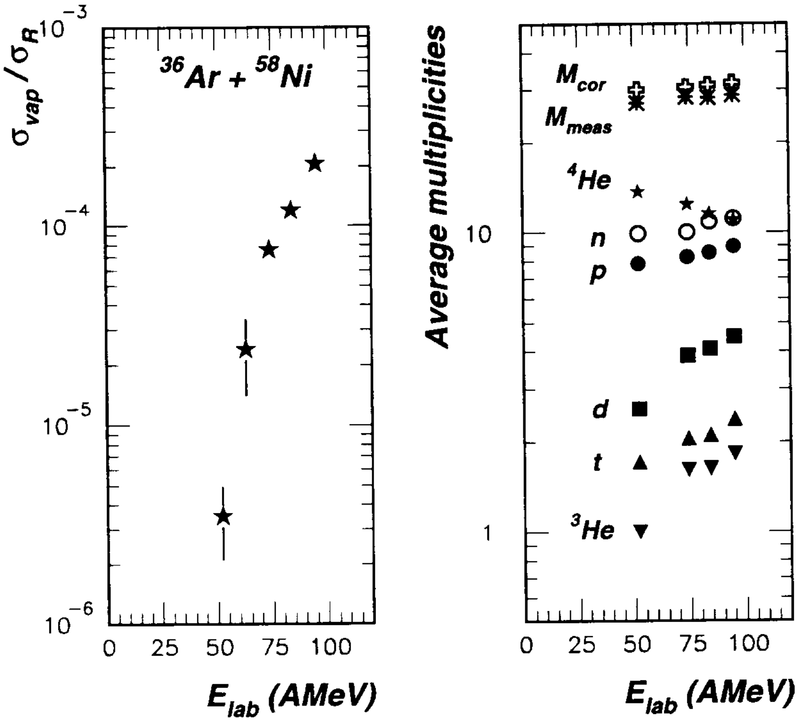

Figure 2: Left: Excitation function for vaporization. Cross-sections are normalized to calculated reaction cross-sections [10]and are not corrected for detection probability (see text). Right: average multiplicities of the different particle species in the vaporization events. Full (open) symbols refer to measured (corrected) values.

expected to form a gas of alpha particles at low densities[12]or from chemical equilibration which is expected in heavy ion collisions at intermediate energies[13].

Basic information on the energetics of the reaction can be derived from energy conservation (table 1). The available energy increases from 12.3 to 22.4 MeV per nucleon when the incident energy increases from 52 to 95 AMeV.

Each of the measured events being completed as described previously, the mass balance of the reaction is readily calculated. Charged particles are emitted with a minimum kinetic energy imposed by the Coulomb repulsion. This Coulomb energy can be estimated assuming two realistic configurations: a compact one corresponding to the Coulomb energy of the liquid drop model and a second one, more dilute, corresponding to an average radius $R=1.6A^{1/3}$ for the sphere which contains all the particles observed in a given event. The sum of the mass balance and of the Coulomb energy (averaged over all events) is subtracted from the available energy per nucleon to derive information on the average kinetic energy, E_k, in excess of the Coulomb energy removed by each particle (table 1). At 52 AMeV this average energy reaches 5.0-6.4 MeV per nucleon, depending on the assumed initial configuration and, assuming thermal equilibrium, is compatible with initial tem-

E_{beam} (AMeV)	52	74	84	95
E_{avail} (AMeV)	12.3	17.5	19.9	22.4
$< E_{coul} >$ (AMeV)	3.5	3.5	3.5	3.5
	2.1	2.1	2.1	2.1
$< Q >$ (AMeV)	3.8	4.1	4.2	4.4
$< E_k >$ (AMeV)	5.0	9.9	12.2	14.5
	6.4	11.3	13.6	15.9

Table 1: For each incident energy are given: the available energy, the Coulomb energy, the mass balance and the kinetic energy of the particles, E_k, in excess of the Coulomb energy (see text). For E_{coul} and E_k the first line refers to a compact configuration and the second line to a dilute one.

peratures in the range 7-10 MeV for surface as well as for volume emission. At 95 AMeV this average energy reaches about 15 MeV per nucleon. This large value then raises the question to which extent this energy is thermalized. The answer to this question should be found in a detailed analysis of the particle energy and angular distributions.

A possible origin of the observed events is a vaporization through a sequential decay process. Calculations have been made in the framework of the decay model of ref.[14]. This code was modified to accommodate very high excitation energy and to incorporate discrete excited levels of light clusters (up to ${}^{8}Be$). Without preequilibrium emission, two mechanisms have been assumed: i) a complete fusion of projectile and target and ii) a deeply inelastic collision with complete energy damping in which the two reaction partners carry an amount of excitation energy proportional to their mass. In fig.3 is given the relative yield of nuclei leading to vaporization as a function of the excitation energy per nucleon, after correction for detector efficiency and selection on Z_{tot} as experimentally performed.

The two hypotheses lead essentially to the same conclusion, namely that vaporization sets in at around 12 MeV per nucleon excitation energy which is very close to the available energy in the system at 52 AMeV bombarding energy. It is known that, for such bombarding energies, a significant number of particles are emitted before full thermal equilibrium of the system, thus reducing its excitation energy[15, 16]. However, large fluctuations in the number of preequilibrium particles are observed, leading to broad excitation energy distributions which may extend up to the available energy, where vaporization can take place. As observed experimentally, the calculation predicts that α particles are more abundantly produced than protons; the other isotope yields are also approximately reproduced. Thus, while keeping in mind that applying a statistical sequential decay model at 12 MeV per nucleon excitation energy is a questionable extrapolation, one can not rule out this process as being at the origin of the vaporization events observed.

In conclusion, the first evidence for the onset of the complete disassembly of a nuclear system into light particles (n, H and He isotopes) is presented. For the ${}^{36}Ar+$ ${}^{58}Ni$ system, it is found that a minimum excitation energy of $\sim$ 12 MeV per nucleon is necessary for

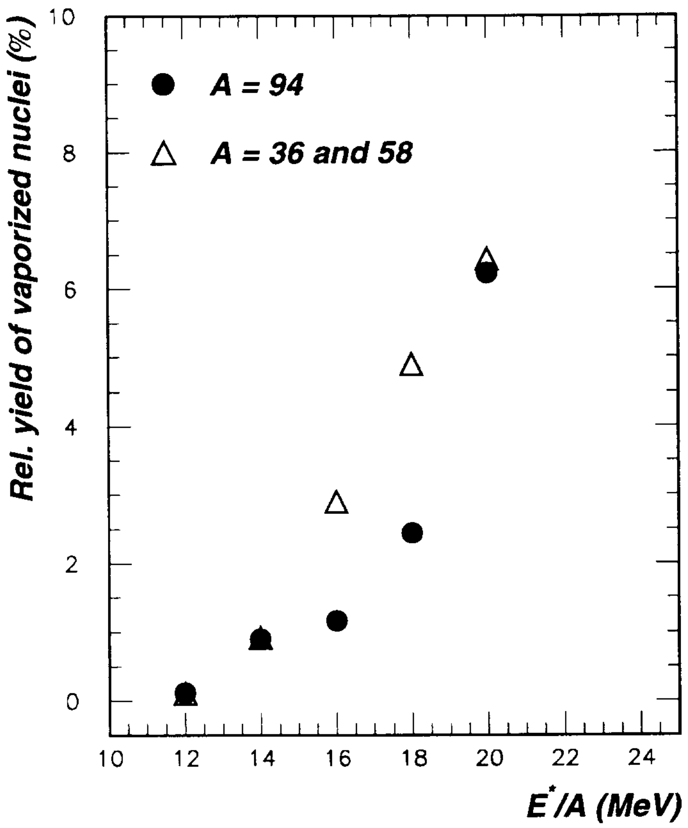

Figure 3: Calculated relative yields of "vaporization" events resulting from the deexcitation of a compound nucleus (closed circles), or of the two partners of a fully damped deeply inelastic collision (open triangles) as a function of the thermal excitation energy of the system.

full vaporizing into light particles. This excitation energy is about twice as large as the energy necessary to break the system with the observed particle distribution where the α particles are the most abundant.

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