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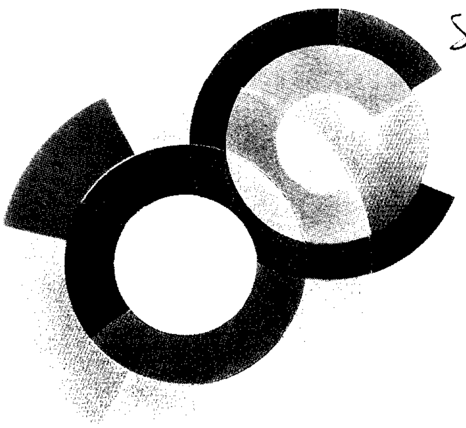

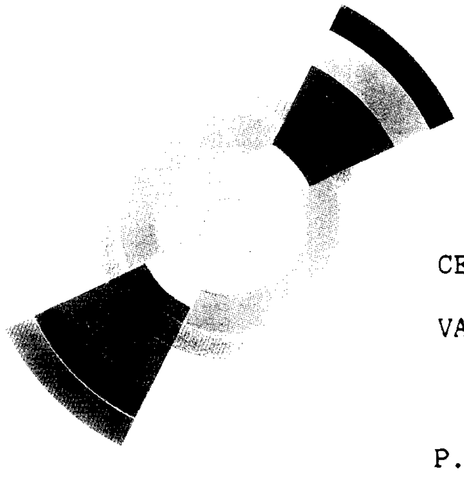

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VAPORIZATION THRESHOLD OF THE Ar+Ni SYSTEM[1]

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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 energy threshold 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. An upper limit for the temperature at which vaporization first occurs is derived.

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[1] Experiment performed at GANIL

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To improve the knowledge of the properties of nuclear matter under peculiar conditions of temperature and pressure, one has, in studying central nucleus-nucleus collisions at intermediate energies, to determine how and at what excitation energy the highly excited nuclear system formed disassembles. At a high enough energy the multifragmentation process is first 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] . When increasing the energy deposit, a second interesting feature, a second transition we should say, 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. Hovewer, the link between this vaporization process and the liquid-gas phase transition in infinite nuclear matter is not obvious and is much debated [6] . Futhermore, finite size effects and the Coulomb force lead to a sizeable reduction in the critical temperature Tc in nuclei [8] . Thus an experimental determination of the temperature at which vaporization sets in 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 [7] , 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 modules of this detector comprise two (ionization chamber-CsI) or three (ionization chamber-silicon detector-CsI) stages, depending on detection angle, for complete identification of charged products on a large energy range.

A unique $193\mu g/cm^2$ ^{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 registered without any bias; at 52 AMeV we could thus 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 figure 1. 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.

Let us now examine the class of events which were defined as vaporization events, without any assumption on the intervening mechanisms. As mentioned earlier these events contain only light charged particles; the safer way to correctly select such events would be to keep only events where the detected charge is greater than 44 (accepting that one helium nucleus may be missing). The statistics would then be too low. Therefore we enlarge our selection with the help of a simulation [12] . 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. We thus search for events for which the probability that a fragment ($Z \geq 2$) 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. 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). It was verified that these rare events do not result from pile-up events.

The first piece of information which can be extracted is the cross-section for vaporization. It becomes sizeable above 52 AMeV and rises sharply to reach some 10^{-4} times the total reaction cross-section at 95 AMeV (fig.2, left part). We can therefore infer that, for this system, the threshold for vaporization is around 50 AMeV.

We can also examine the isotopic composition of these events. For this, we have plotted in figure 2 (right part) the average measured multiplicity of each isotope and their sum (M_{meas}). 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.) according to the measured yields , neutron multiplicities are deduced from atomic mass conservation and found very close to proton multiplicities. The most striking result is the large yield of alpha particles observed. At least three explanations can be invoked. The most simple concerns the symmetry of the total system ($N \sim Z$) which can favour the emission of alpha particles. A second explanation can be found if regarding alpha particles as deexcitation products of low Z primary excited fragments. A third one, more speculative, would refer to a property of nuclear matter which is expected to form a gas of alpha particles at low densities [12] .

We can try now to give some information on the energetics of the reaction. This is shown in figure 3. Each of the measured events being completed as described previously, the mass balance of the reaction is readily calculated (full circles). Charged particles cannot be emitted without kinetic energy, they have at least the Coulomb repulsion. This 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 of each event. The sum of the mass balance and of the Coulomb energy amounts to 5.8-7.9 MeV per nucleon, depending on the incident energy (bars in fig.). These quantities are averages over all the events. They can be compared to the available energy per nucleon (stars in fig.) to derive information on the average kinetic energy (without Coulomb energy) removed by each particle. This average value ϵ is 5.1-6.5 MeV at the energy threshold and reaches 14.5-15.9 MeV at the higher bombarding energy. This large increase is very likely a signature of the prominence of nonequilibrium and dynamical effects when the incident energy moves from 50 to 100 AMeV. Conversely an upper limit for temperature at which vaporization appears can be deduced, at 52 AMeV, assuming a complete vaporization of the total system after it thermalizes. The temperature of the system is then half the average kinetic energy of each particle and reads:

$$T = (\epsilon * A_{tot})/(2 * M_{tot})$$

where M_{tot} is the average corrected particle multiplicity (including neutrons), which is equal to 39 and $A_{tot} = 94$ the total mass of the system. Upper limits for the temperature of vaporization are thus found in the range 6.1-7.8 MeV, depending on estimates of the

Coulomb energy. These values are in good agreement with the saturating temperature (7 MeV) experimentally deduced for hot nuclei [13, 14]. More precise information will be obtained from energy and angular distributions of the particles.

In conclusion, we have been able to establish, for the first time, an energy threshold for the complete vaporization of a nuclear system into light particles (n, H and He isotopes). From the composition of the vaporization events an upper limit for the temperature at which vaporization takes place for the $^{36}Ar+\ ^{58}Ni$ system, was deduced. This finding will have to be incorporated in nuclear models attempting to describe the disassembly of hot nuclei.

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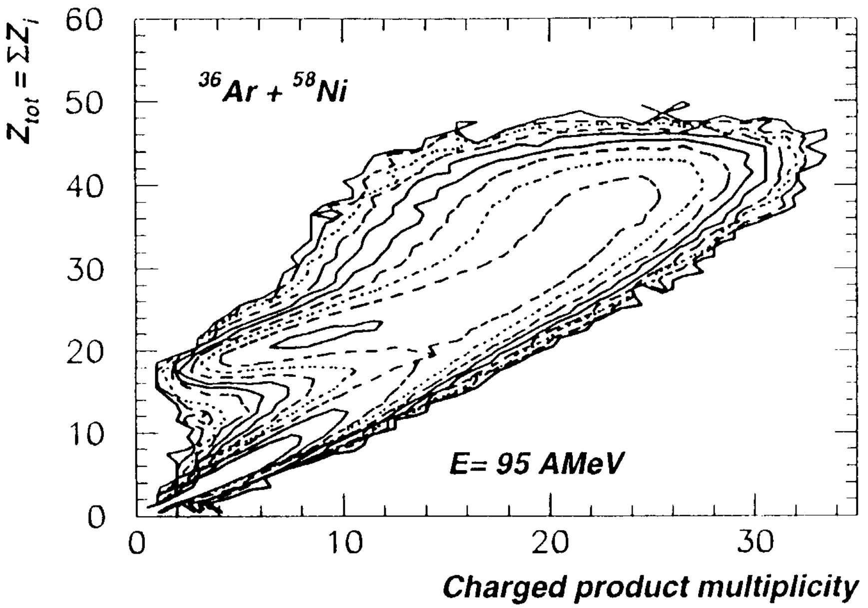
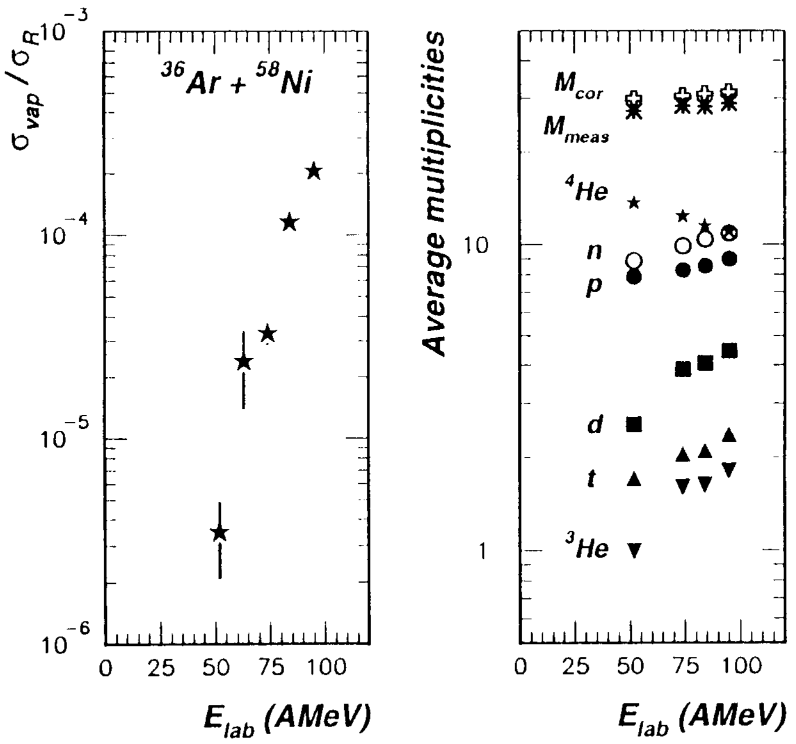
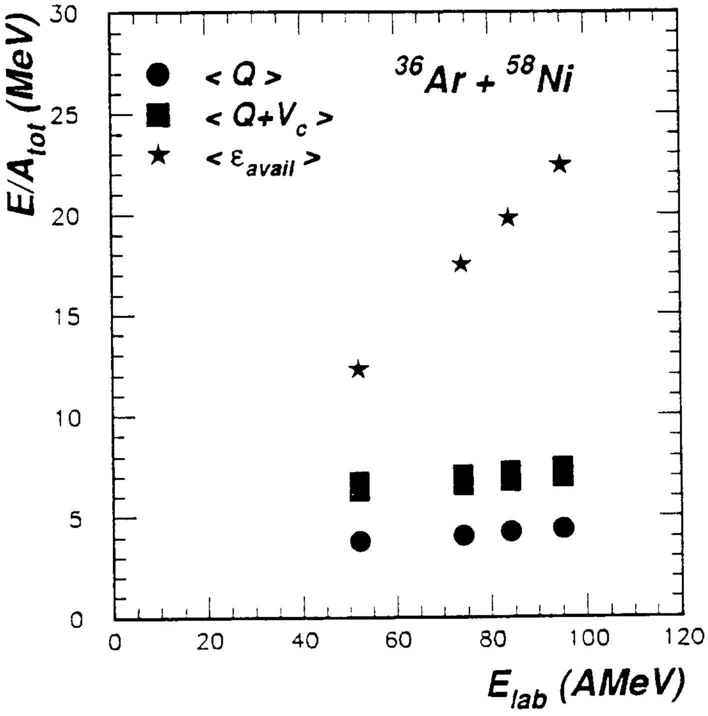
Figure 1: Measured relation between charged product multiplicity and total detected charge. The total charge of the system is $Z_{tot} = 46$. Eleven contour levels are drawn (2 to 2048 events)

Figure 2: Left: Excitation function for vaporization. Cross-sections are normalized to calculated reaction cross-sections ([10]). Right: average multiplicities of the different particle species in the vaporization events. Full (open) symbols refer to measured (corrected) values.

Figure 3: Energetic properties of the vaporization events: mass balance, mass balance + Coulomb energy and available energy in the system at the different bombarding energies (see text).


$^{36}Ar + ^{58}Ni$
E= 95 AMeV
$Z_{tot} = \Sigma Z_i$
0
10
20
30
40
50
60
0
10
20
30
Charged product multiplicity


σ_{vap} / σ_R
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$^{36}Ar + {}^{58}Ni$
0
25
50
75
100
E_{lab} (AMeV)
Average multiplicities
10
1
M_{cor}
M_{meas}
^4He
n
p
d
t
^3He
0
25
50
75
100
E_{lab} (AMeV)


E/A_tot (MeV)
30
25
20
15
10
5
0
● < Q >
■ < Q+V_c >
★ < ε_avail >
36Ar + 58Ni
0
20
40
60
80
100
120
E_lab (AMeV)