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The INDRA 4π detector and its scientific program.

F. SAINT-LAURENT
GANIL, BP 5027, 14021 Caen, FRANCE
*and the INDRA Collaboration**

Invited talk at the International School-Seminar on Heavy Ion Physics, May 10-15, 1993, Dubna, Russia

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Abstract : The INDRA 4π multidetector has been built by four laboratories (DAPNIA-Saclay, GANIL-Caen, IPN-Orsay, LPC-Caen) with the technical collaboration of the LAL-Orsay. This detector for light charged particles and heavy fragments is mainly dedicated to the study of the deexcitation of hot nuclear systems formed in nucleus-nucleus collisions in the intermediate energy domain under peculiar conditions of temperature or compression, and especially to the study of the multifragmentation. After a brief description of the detector and its capabilities to identify particles and fragments, the scientific program for the next three years will be presented.

I. Introduction

Very hot nuclear systems formed in the intermediate energy heavy ions collisions can decay by emitting a large number of light particles and fragments. Detailed studies of the multi-fragment decay of excited systems are still rather limited, especially concerning the existence, the origin and the characterization of a simultaneous multifragmentation. These studies require an event by event detection capability of high precision and efficiency. Many of the methods and models used in the analysis of this physics also require a proper determination of the size of the excited system as well as a precise measurement of the size (charge, mass) of the decay products and a measurement of their energy. The community of physicists working in this area at the GANIL facility decided in 1988 to build a 4π charged products detector with very high capabilities. The very efficient detection technics - Ionization chamber, silicon and scintillator detectors - were associated to satisfy the main goals of the detector : High geometrical efficiency (≈90%), low identification threshold (1 MeV.A), mass identification of p, d, t, ^{3}He and ^{4}He up to ≈150 MeV, charge identification up to Z=30 [1]. The first part of the paper describes the detector and its electronics. The physics program, which has been started in march 1993 at GANIL, will be described in the second part.

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II. Description of INDRA

II.1 The detector

The detector, which has to operate under vacuum, can be schematically described as a series of 17 rings with an axial symmetry around the beam axis, each ring being divided into a varying number of cells (from 8 to 24). A detailed description can be found in ref.2. Table 1 and figure 1 give the geometrical outline of the detector. The solid angle subtended by each cell varies by a factor of about 100 from forward to backward angles to compensate the forward peacked angular distributions of emitted particles. The granularity of the array permits to detect with convenience light charged particles multiplicities of the order of 40 and heavier products multiplicities of the order of 10.

	Phoswich NE102 - NE115							
Ring N°	θ_{min} (°)	θ_{max} (°)	N	$\Delta\phi$ (°)	e NE102 (cm)	e NE115 (cm)	$\Delta\Omega$ (msr)	d (cm)
1	2	3	12	30	0.5	25	0.45	104

	CsI						Si	Ionization Chamber				
Ring N°	θ_{min} (°)	θ_{max} (°)	N	$\Delta\phi$ (°)	e (cm)	$\Delta\Omega$ (msr)	e (µm)	$\Delta\phi$ (°)	N	n CsI	d (cm)	$\Delta\Omega$ (msr)
2	3	4.5	12	30	14	0.82	300	30	12	3	65.5	3.4
3	4.5	7	24	15	14	1.29	300					
4	7	10	24	15	14	2.10	300	30	12	4	31.5	11.4
5	10	14	24	15	14	3.59	300					
6	14	20	24	15	10	8.00	300	30	12	4	25	40.4
7	20	27	24	15	10	12.2	300					
8	27	35	24	15	10	18.7	300	30	12	4	12	96.0
9	35	45	24	15	10	29.3	300					
10	45	57	24	15	8	41.7	No	30	12	4	12	187
11	57	70	24	15	8	52.0	No					
12	70	88	24	15	6	79.8	No	30	12	2	12	160
13	92	110	24	15	5	79.8	No	45	8	3	12	239
14	110	126	16	22.5	5	93.5	No	45	8	4	12	340
15	126	142	16	22.5	5	76.6	No					
16	142	157	8	45	5	99.1	No	45	8	2	12	159
17	157	176	8	45	5	59.5	No					

Caption :
N : number of detectors per ring
e : Thickness of detector
$\Delta\Omega$: Solid angle of detector
n : number of CsI behind an ionisation chamber
d : distance from target
θ : polar angle
ϕ : azimuthal angle

Table 1.

INDRA

DAPNIA (Saclay)
GANIL (Caen)
IPN (Orsay)
LPC (Caen)

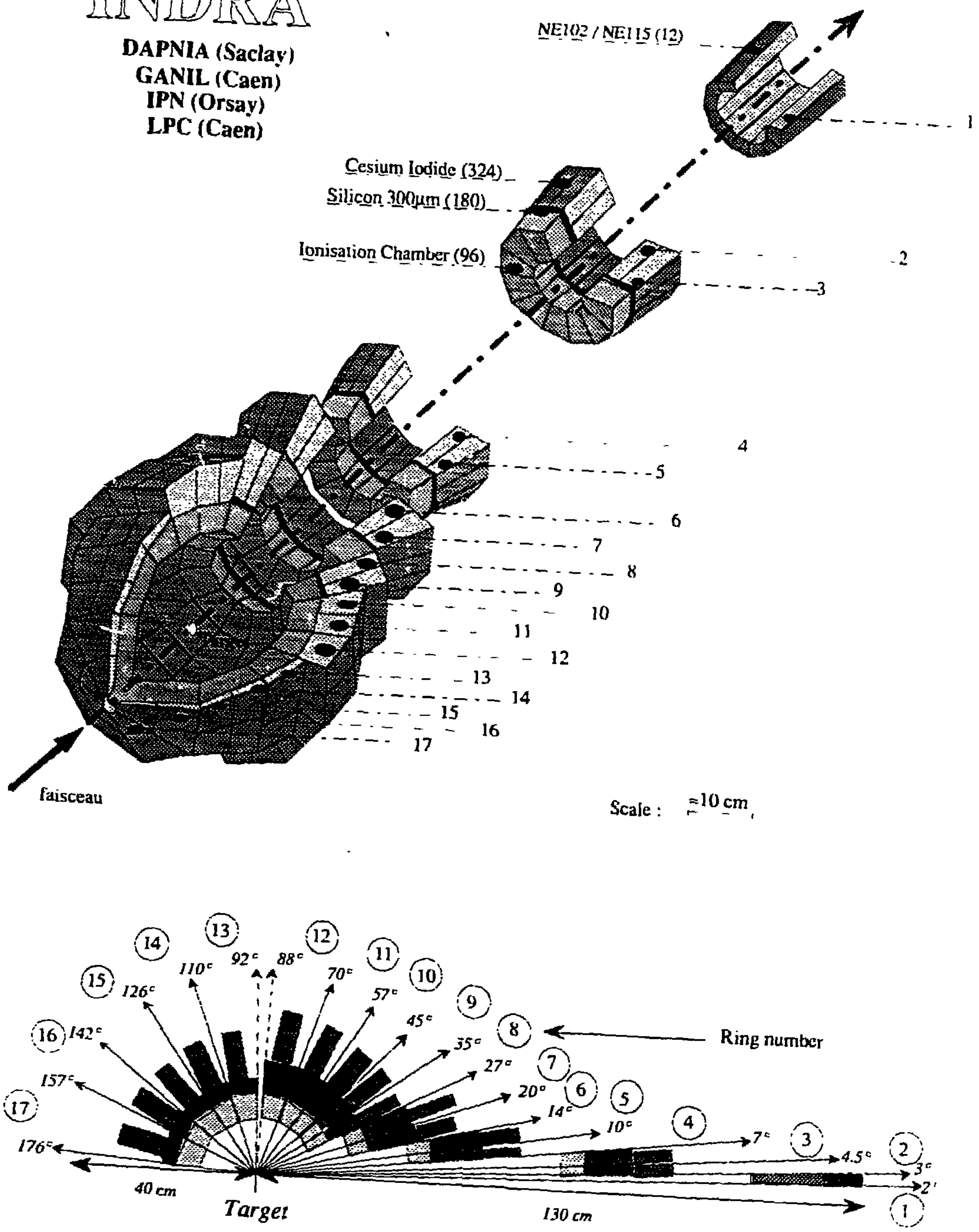

Figure 1.

Three standard detection cells, depending on the detection angle, were defined for INDRA :

Ring 1 ($2° \leq \theta_{lab} < 3°$) : 12 phoswich detectors (NE102+NE115) for the high counting rate generally found for these very small detection angles. For this ring, the energy thresholds are rather high due to the 0.5mm fast NE102 plastic thickness.

Rings 2 to 9 ($3° \leq \theta_{lab} < 45°$) : each cell is made of 3 successive detection layers - Ionization chamber (IC), Silicon detector and CsI(Tl) scintillator. Figure 2 shows a typical module of these rings. The ionization chamber (5 cm deep with radial electric field) operate either with CF_4 gas or with C_3F_8 gas at a pressure up to 50 torr. The IC is followed by 300 μm planar silicon detectors (3 or 4 depending on the ring number) made on the same wafer to reduce as much as possible the dead zones. Each Si detector is backed by a CsI(Tl) scintillator, 14 cm to 10 cm deep, depending on the ring, associated to a photomultiplier.

Rings 10 to 17 ($45° \leq \theta_{lab} < 176°$) : for these rings the silicon detectors are suppressed because the kinetic energy range of the detected fragments is reduced. To ensure the calibration of the CsI(Tl) scintillators, a telescope (Si 75 μm-Si(Li) 2 mm thick) is inserted into one cell of each ring.

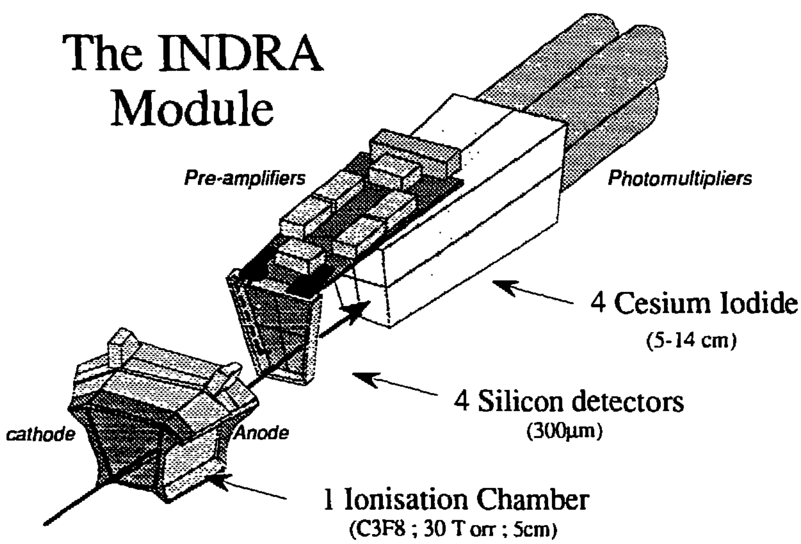

Figure 2.

The making of a 4π ionization chamber layer with a high geometrical efficiency represents the first challenge and certainly the most original feature of INDRA. Two different kinds of chambers have been designed. At forward angles ($3° \leq \theta_{lab} < 27°$), the three structures used have been made by moulding. Each structure with a common gas flow is divided into 12 ionization chambers (see fig. 3). At larger angles, two similar structures with 36 and 24 cells have been built using electronic board circuits glued together (fig. 4). 2 μm thick metallized mylar foils are glued in front of (cathode) and behind (anode) each structure.

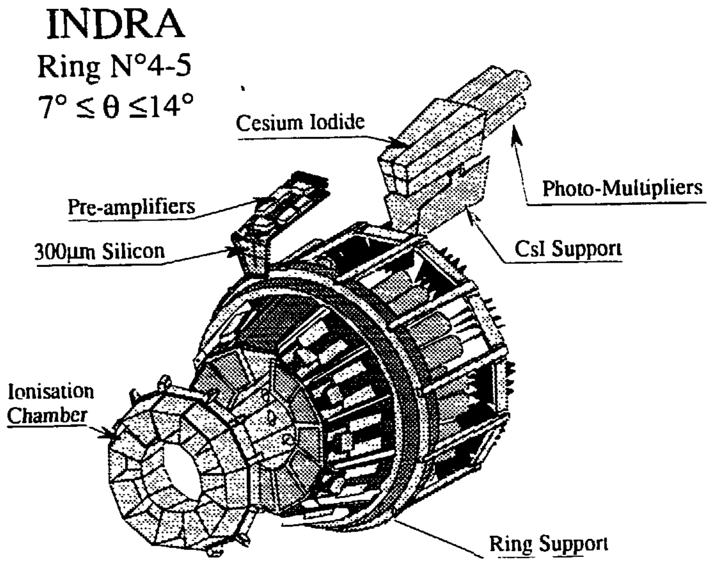

Figure 3.

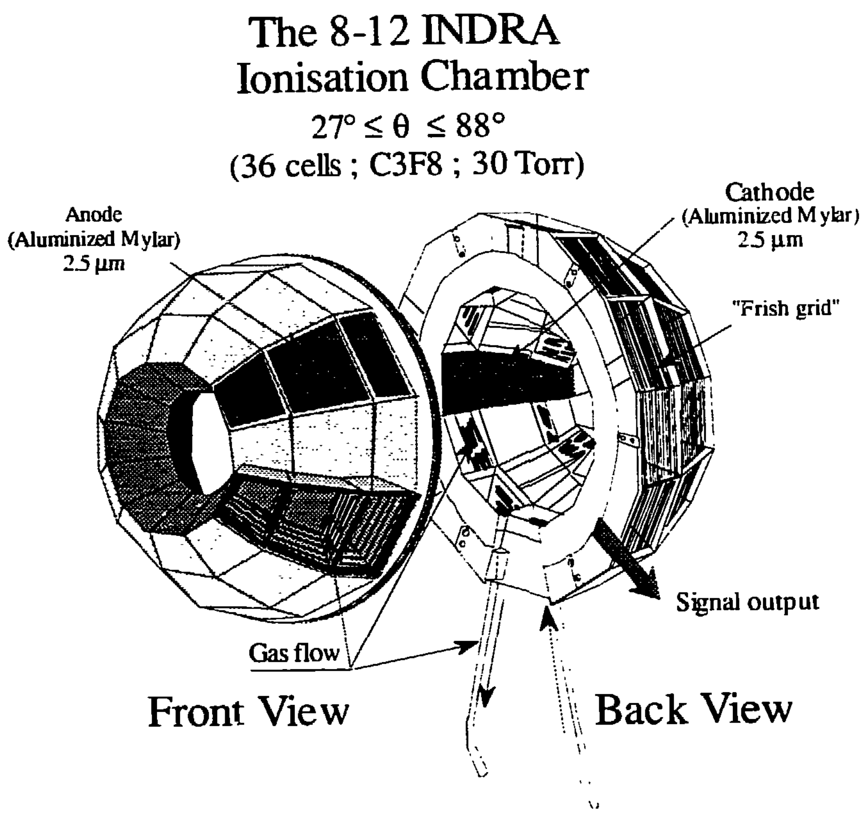

Figure 4.

The CsI(Tl) detectors are used alone for light particle mass identification by exploiting the pulse shape discrimination techniques, and in association with the other detector types for fast fragments detection. Special care was paid for the material quality of the scintillator and for the voltage distribution bases (low noise, good linearity) associated to four different types of green extended photomultipliers.

II.2 The electronics

The second challenge for the INDRA detector was the huge dynamical range needed for the electronics. The ionization chambers electronic must be able to detect signals ranging from about 150 KeV to 250 MeV. For silicon detectors the dynamical range which has to be covered exceeds 3000 (from about 1 MeV to 3-4 GeV). These requirements also implied that cross-talk be kept below that level and that surrounding noise be minimized by very efficient earthing and shielding. Moreover the large number of detectors to handle asked for a highly integrated electronics. Then the electronics were studied and built by the laboratories of the collaboration. Complete integrated modules, in VXI standard, for CsI and phoswich detectors, and semi-integrated electronics, in CAMAC and VXI, for ionization chambers and Si detectors were developped. All the electronics is located only a few meters from the detector and is remote controlled by computer, including a computer controlled multiplexing to visualize analogical and logical signals on oscilloscopes.

To solve the huge dynamical range needed for IC and Si detectors, the traditional peak sensitive encoding was replaced by a charge integration method with two sensitivities (G and G×16). The noise level during normal operation is kept below the millivolt level. Figure 5 illustrates the results obtained with Si-CsI identification for Xe projectile on Ag target at 45 MeV/u. With the low gain G, the Z identification is good enough to separate the Z lines up to at least Z=56 (fig. 5a). The elastic scattering peak corresponds to an energy loss of about 2.1 GeV in the Si detector. In fig. 5c the result of the high gain encoding is shown for the same telescope, and fig. 5d shows the matrix when only the first 256 channels of the large gain are displayed : hydrogen isotopes losing 0.7 MeV in the ΔE are identified.

The rather large number (= 2000) of analogical channels imposes a specific choice of triggering system. The standard type of trigger - master decision allowing a subsequent opening of the encoding gates - is precluded because it requests long delay lines on every channels which may deteriorate the signals. So a new type of trigger, named "asynchronous", has been developped : each tagged channel stores its own analogical signal whatever the master decision is, and after a delay of few microseconds resets itself. If a master acceptation occurs, the reset is inhibited, allowing the encoding of the stored information. The master decision is elaborated by a multiplicity signal built-up from sub-groups of detection modules (for instance a giving ring or a set of rings).

II.3 Calibration of the detectors.

The stability of the electronic and of the photomultiplier gains are continuously controled by a pulser and a laser light generator. The absolute calibration of the detectors are achieved by using the secondary beam facilities of GANIL. At small scattering angles ($\theta_{lab} < 10°$), elastic scattering of secondary beams created by the fragmentation of the primary beam on a Au target is used to calibrate phoswich detectors as well as IC-Si-CsI telescopes. Elastic scattering of low energy beams (5 to 9 MeV/u) is,used also to calibrate Si detectors up to 45° and to measure the pulse high defect. Finally, light particles beams, generated by the stopping of a high intensity ^{16}O beam in a very thick C target, are elastically scattered on a thick C or Ta target to calibrate CsI scintillators. The intensity of the produced p, d, t, ^{3}He, ^{4}He secondary beams - 10^{5} pps - is high enough to allow the calibration of scintillators up to 180° within a couple of hours.

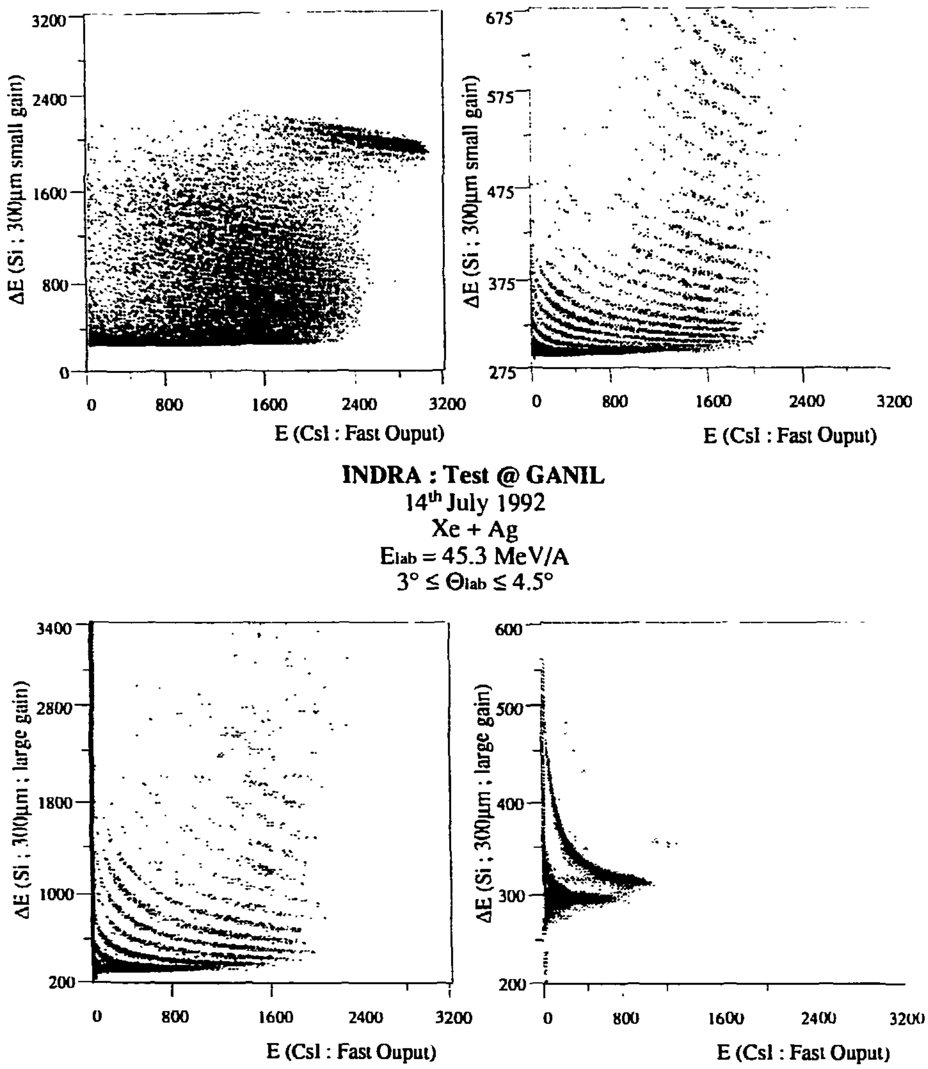

Figure 5 : ΔE-E matrices obtained with Si detector signal versus the CsI fast component.

III. Physics program of INDRA

For the next three years our program is mainly devoted to an exhaustive study of the decay of hot nuclear systems, and especially to the study of multifragmentation processes [3]. The influence of the dynamics on the multifragmentation will be investigated in details. At the same time, the dynamics of the collisions will be studied through flot measurements. This program will be followed by a study of the energy partition of damped binary reactions.

III.1 Multifragmentation of compressed nuclear systems.

In the Fermi energy domain and for central collisions, dynamical calculations predict the occurrence of a compression phase in the early stage of the collisions [4,5]. Figure 6 illustrates the dynamical behaviour of the average density as predicted by these models. At low bombarding energy (fig. 6 a), after the compression phase, the system goes back to normal density with a period which depends on the nuclear incompressibility modulus K_∞ (Fig. 6 b). One must notice that the characteristic time of this compression phase is of the order of three times the energy relaxation time, therefore the systems are nearly thermalized at the end of this phase. When increasing the incident energy, the system can expand (fig. 6 a) and never come back to normal density. The more dilute the expansion configuration is, the slower is the path back to normal density, until a limit where a nuclear break-up occurs. At that point, a simultaneous multifragments emission of the thermalized dilute system (ρ = 0.2-0.3 ρ_0) is expected to occur in the range 100-200 fm/c after the beginning of the collision [6].

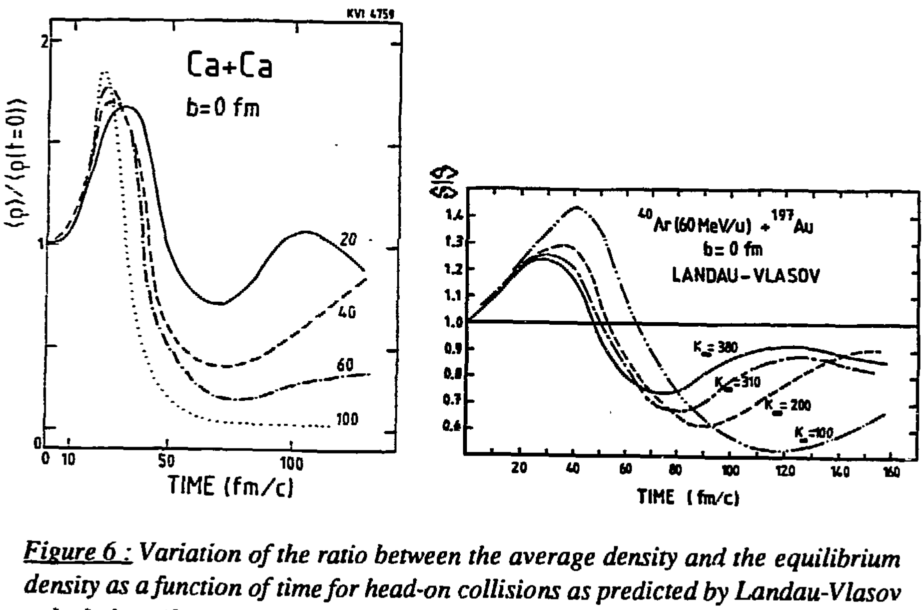

Figure 6 : Variation of the ratio between the average density and the equilibrium density as a function of time for head-on collisions as predicted by Landau-Vlasov calculations (from refs. 5,6).

The statistical decay of very excited nuclei at low density has been theoretically studied by the Copenhagen group [7] and the Berlin group [8]. They have found that the average multiplicity of intermediate mass fragments (IMF) should be strongly enhanced when the excitation energy of the system exceeds 3.5 MeV/u, as compared with the prediction of a binary sequential decay model [9] (fig 7). Experimental evidences of such large IMF multiplicities have been already reported [10]

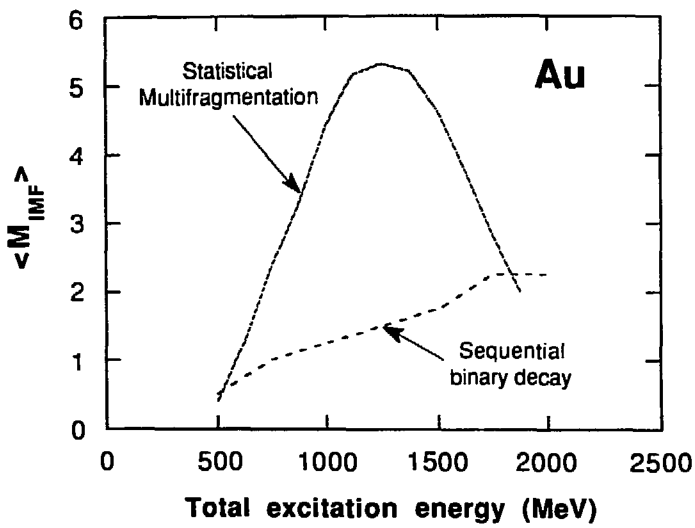

Figure 7 : Average intermediate mass fragment multiplicity as a function of the total excitation energy of a Au nucleus as predicted by a multifragmentation model [7] (full line) or by a binary sequential model [9] (dashed line).

Two sets of experiments are planned to be studied with INDRA :

- Symmetric systems ranging from ^{12}C+ ^{12}C up to ^{197}Au+^{197}Au at 30 MeV/u. For these systems the compression-expansion effect is predicted to be maximized. Moreover, the excitation energy per nucleon is expected to be near the same at a given incident energy and a given impact parameter, whatever the total mass of the system is. A deviation of final products mass distribution as a function of the total mass of the system should be a clear signature of nuclear medium effects involved in the multifragmentation process.

- The ^{129}Xe+^{nat}Sn, ^{58}Ni+^{197}Au and Mo+Sm assymmetric systems, leading to about the same total mass A ≈ 250, will be studied. The aim is to focus on the possible influence of the dynamical compression-expansion phase on the multifragmentation process by varying the mass assymetry of the entrance channel, ie the initial compression rate.

III.2 Multifragmentation of very heavy composite systems.

Few years ago, theoretical calculations [11] have shown that Coulomb repulsion can induce the instability of a hot nucleus at normal density when its temperature raised beyond a limiting value. The calculation, using a finite version of the liquid drop model, supposes a hot necleus in equilibrium with an external vapor. Coulomb repulsive force has been found to be at

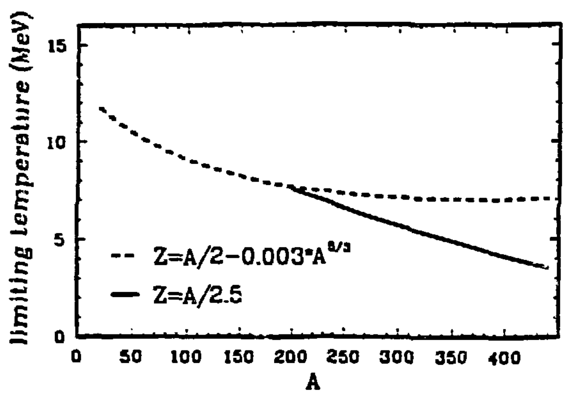

***Figure 8 :** Temperature limit of nuclei as a function of their moss (from ref. 11). The dashed line corresponds to nuclei along the b-stability line and full line refers to composite nuclear systems which can be produced in very heavy nucleus-nucleus collisions.*

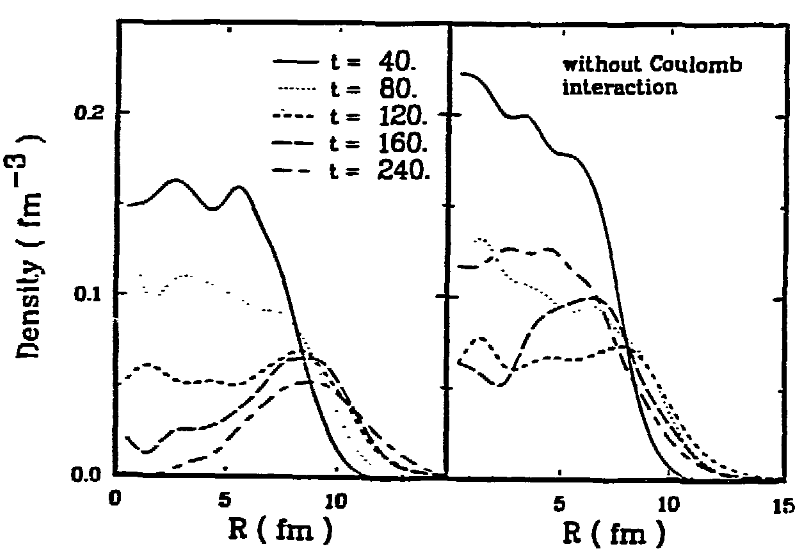

***Figure 9 :** Density profiles at different times (in fm/c) as predicted from Landau-Vlasov simulations for the $^{155}Gd + {}^{238}U$ system at 35 MeV/u (from ref. 3) when Coulomb interaction is included (left-hand part) or switched off (right-hand part).*

the origin of this instability. The temperature value at which the Coulomb instability takes place is related to a balance between the Coulomb, the surface and the bulk nuclear energy. Its depends on the total mass of the composite system (fig. 8). When the instability takes place, an unstable bubble nucleus is expected to be formed.

Recent dynamical calculations using the Landau-Vlasov equation have been performed for central collisions between ^{155}Gd and ^{238}U at a bombarding energy of 35 MeV/u [12]. A formation of such a nuclear bubble is observed (fig. 9). Then a break-up into fragments occurs around 160 fm/c after the beginning of the collision.

A program including the study of Gd+U, Au+Au and U+U systems at an incident energy around 30 MeV/u is planned.

III.3 Flot measurements.

Dynamics studies of nucleus-nucleus collisions can give informations on the nucleon-nucleon cross-section σ_{NN} inside the nuclear matter and on the nuclear equation of state through the incompressibility modulus K_∞.

The directed collective motion of nucleons and clusters emitted at the beginning of the collision (sidewards flow) is a way to provide informations on the dynamics of the collision. A specific analysis method has been developped to study the sidewards flow, via the component of the transverse momentum of mid-rapidity nucleons and clusters in the reaction plane (named flow). At low bombarding energy (few tens of MeV/u), the interaction is dominated by the attractive mean field. Particles and fragments have been shown to be deflected to negative angles. Conversely, at high energy (over 100MeV/u), the interaction is dominated by the nucleon-nucleon collisions, leading to positive deflection angles attributed to a repulsive momentum transfer in the interacting region. Semi-classical calculations [13] have shown that the energy dependence of the flow parameter and the energy at which the flow vanishes (balance energy) are sensitive to σ_{NN} inside the nuclear matter and to the incompressibility modulus K_∞.Depending on the system, the 20-150 MeV/u bombarding energy region, has to be carefully studied to determine the balance energy and the energy dependence of the flow parameter. Light systems has been already studied in details over a large incident energy range, and including an impact parameter selection [14].

The $^{36}Ar+^{58}Ni$ system has just been studied at an incident energy ranging from 32 to 95 MeV/u with INDRA detector. Because the theoreticians asked for a study over a very large bombarding energy range, the $^{58}Ni+^{58}Ni$ system will be studied between 30 MeV/u and 400 MeV/u by coupling results obtained at GANIL facility with INDRA and at SIS facility using FOPI detector.

III.4 Excitation energy partition in damped binary collisions.

Damped binary reactions have been extensively studied at low energy to derive information on the excitation energy partition and consequently on relaxation time for temperature equilibration in nuclear matter.

First results in the 30 MeV/u energy domain have already been reported [15]. In the 50-100 MeV/u bombarding energy range, it is much more complicated to disentangle the two evaporative parts of the binary partners and the stronger and stronger preequilibrium component. A 4π device is needed not only to select binary reactions, but also to derive from complete events information on the excitation energy partition between the two partners and on the energy removed by preequilibrium process.

A program to study the energy partition will be started in the near futur with the INDRA detector.

IV. Conclusion

Begun in 1990, the complete INDRA detector has been successfully used for a first set of experiments in march and april 1993. The Ar+KCl, Ar+Ni, Xe+Sn and Gd+U systems have been studied over the 30-95 MeV/u energy range. A detailed study of the onset of multifragmentation as a function of the size of the system, the influence of the initial compression and of the Coulomb forces on the time evolution and on the decay processes of the hot nuclear systems formed, are the investigated fields of these experiments.

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