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FIRST RESULTS WITH THE 4π INDRA DETECTOR*

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Abstract : The new 4π INDRA detector, mainly dedicated to the study of hot nuclear systems decaying by multifragmentation, is available for experiments since the beginning of 1993. After a short review of the planned physics program and a brief description of the characteristics of the detector, the first results are presented and compared with the predictions of theoretical calculations.

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* Experiment performed at GANIL

1. Introduction

It is now well established that multifragment emission is an important decay channel for strongly excited nuclear systems formed in heavy ion collisions at intermediate bombarding energies ($10 < E_{lab} < 100$ MeV/nucleon) [1-6]. The study of such a multifragment emission is essential as it may provide crucial information on the properties of nuclear matter under extreme conditions of temperature and pressure. Using first generation 4π detectors [7-10], some answers have been brought on some specific points as, for example, the extraction of time scales of involved mechanisms [12-15], or the onset of expansion effects [16-17]. Nevertheless, the answers are still rather sparse and somewhat contradictory. Furthermore, in order to disentangle the role of various parameters such as the bombarding energy (total and per nucleon), the mass asymmetry, the total mass of the system, systematic measurements are needed and the extraction of unambiguous signatures of multifragmentation requires more and more efficient devices allowing for the detection of complete events [17-18].

In this paper, we report on the first results obtained with INDRA [18]. The physics program and the description of the detector are given in sects. 2 and 3, respectively. Data and comparisons with theoretical predictions are presented in sects. 4 and 5 and the conclusions in sect. 6.

2. The physics program of INDRA

As already described [19], this program is mainly devoted to the study of the properties of strongly heated and compressed nuclear matter. The main topics are briefly recalled in this section.

2.1. Multifragmentation

Theoretical investigations predict that the multifragmentation process is closely linked to reaction trajectories in the pressure-density plane crossing regions of reduced nuclear density [20-21]. They show the occurrence of a fast compression phase at the beginning of the collision, followed by an expansion phase in regions of low nuclear density. Depending on the bombarding energy, either the nuclear system goes back to normal density , or it enters in a mechanically unstable region. If the nuclear system stays long enough in that region (spinodal region), dynamical instabilities can develop and lead to a simultaneous break-up of the expanded system. Such a process is expected to occur at bombarding energies of $\cong 40 - 60$ MeV/nucleon, depending on the total mass of the system, on a time scale of the order of 100 - 200 fm/c. At even higher bombarding energies, a complete disassembly of the nuclear system is predicted (vaporization). Besides this dynamical description, multifragmentation is also expected in statistical models [22-25]. In order to disentangle between these quite different approaches, the light systems Ar + KCl, Ar + Ni and Ni + Ni, as well as heavier ones like Xe + Sn and Ni + Au, have been (or will be) measured at several bombarding energies.

Very heavy systems have also been considered. In this case, static calculations using a finite temperature version of the liquid drop model [26] have shown that, due to Coulomb repulsion, hot nuclei become unstable as soon as the temperature is raised above a limiting value. As the surface tension decreases with increasing temperature, the Coulomb repulsion and the internal pressure dominate, giving rise to an instability. In case of very heavy systems, the limiting temperature is reached at rather low bombarding energies, for which compression can be neglected. Similar features are revealed in dynamical calculations [27-29]. For example, in [29], Landau-Vlasov calculations performed for the 35 MeV/nucleon Gd + U reaction for central collisions predict the formation of bubble nuclei breaking up in fragments after about 160 fm/c. Such Coulomb or surface instabilities will be explored by studying the heavy nuclear systems Gd + U, Ta + Ta and U + U at incident energies $\cong 25 - 40$ MeV/nucleon.

2.2. Collective flow of nuclear matter

Another aspect of the physics program is the study of the collective flow of nuclear matter at intermediate energies. Recent experimental results have been obtained on the component of the directed collective flow in the reaction plane, the so-called "sidewards" flow [30, 33-34]. Above the Fermi energy, the nucleon-nucleon (N-N) collisions play an increasing role in the interaction between the nuclei. As a consequence, due to repulsive N-N collisions, nucleons and fragments escaping from the interaction zone are deflected to positive angles. On the other hand, below the Fermi energy, the interaction is governed by the attractive mean field, and the emitted particles are deflected to negative angles. The energy and impact parameter dependences of collective flow have been studied theoretically [35-38]. Comparisons between experiments and predictions reveal that the calculated values are sensitive to the N-N cross section σ_{NN} in nuclear medium and, to a lesser extent, to the equation of state through the incompressibility modulus K. Of special interest is the determination of the balance energy at which the flow disappears, as well as the measurements of the longitudinal component of the collective flow and the azimuthal particle distributions which yield additionnal pieces of information for the understanding of the dynamics of the reaction [31-32, 34].

For this purpose, the symmetric Ni + Ni system will be studied over a large bombarding energy domain, ranging from 30 up to 400 MeV/nucleon, by a collaboration using INDRA at GANIL and FOPI at SIS.

3. Description of INDRA

A detailed description of the detector can be found elsewhere [18]. Its main characteristics will only be briefly recalled, and emphasis will be put about the energy calibration procedures.

3.1. The detector and the electronics

INDRA is a powerful 4π detector composed of 336 modules, with solid angle coverage close to 90 % of 4π, very low energy thresholds (1 MeV/nucleon) , isotopic identification of hydrogen and helium nuclei and full element identification of heavier fragments ($Z \geq 3$).

The detector, designed to operate under vacuum, has an axial symmetry around the beam axis. It consists of seventeen rings. The first ring is made up of twelve plastic phoswiches (500 μm thick NE102 and 25 cm thick NE115) identifying fast heavy ions between 2 and 3 degrees with high counting rates. Rings 2 to 9, located at angles between 3 and 45 degrees, are made each of twenty four modules, each module being a stack of three different detectors : a gas ionization chamber, followed by a 300 μm thick Si detector, divided into four independent detection areas, each Si detection area being backed by a CsI scintillator with a phototube directly glued on it. At larger angles, between 45 and 176 degrees, fast heavy ions are not expected and Si detectors have been removed, thus rings 10 to 17 are composed with modules of only two detectors, an ionization chamber and a CsI scintillator. For energy calibration purpose, a Si telescope has been inserted between an ionization chamber and the corresponding CsI scintillator of rings 10 to 17.

Because of the large number of detectors involved and of the huge dynamical range needed for both the ionization chambers (signals ranging from 150 keV to 250 MeV) and the Si detectors (from about 1 MeV to 3-5 GeV), dedicated integrated electronics has been developed. For this purpose, the new VXI standard has been adopted. All the electronics is located in the experimental cave close to the detector, and is remote-controlled by computer.

3.2. Energy calibrations

Special care has been given to the energy calibration of the detector. Two difficulties had to be overcome : to calibrate the different detectors over a huge dynamical energy range (from a few MeV up to several GeV), and to perform the calibrations without dismounting the detectors, as the calibration runs are intimately connected with the data taking periods.

The various calibration procedures took advantage of the GANIL facilities. The measurement of the elastic scattering of low energy heavy ion beams (7-9 MeV/nucleon) on a heavy gold target allows for the simultaneous calibration of all the 300 μm Si detectors, located at angles smaller than 45 degrees. Since these low energy scattered ions are stopped in the Si detectors, an absolute energy calibration is thus realized as well as measurements of pulse height defects. Moreover, the very forward detectors, Si detectors and phoswiches, benefit of additionnal calibration data with the measurements of the elastic scattering of high energy heavy ion beams, as well as secondary beams.

Specific measurements were dedicated to the absolute energy calibration of the CsI scintillators. The basic principle relies upon the measurement of the elastic and inelastic scattering of secondary light particles produced by the break-up of an intense 95 MeV/nucleon ^{16}O beam on a very thick C target. These particles are then momentum selected by a magnetic spectrometer and finally scattered onto a thick C or Ta target (a few mg/cm^2 thick) in the reaction chamber.

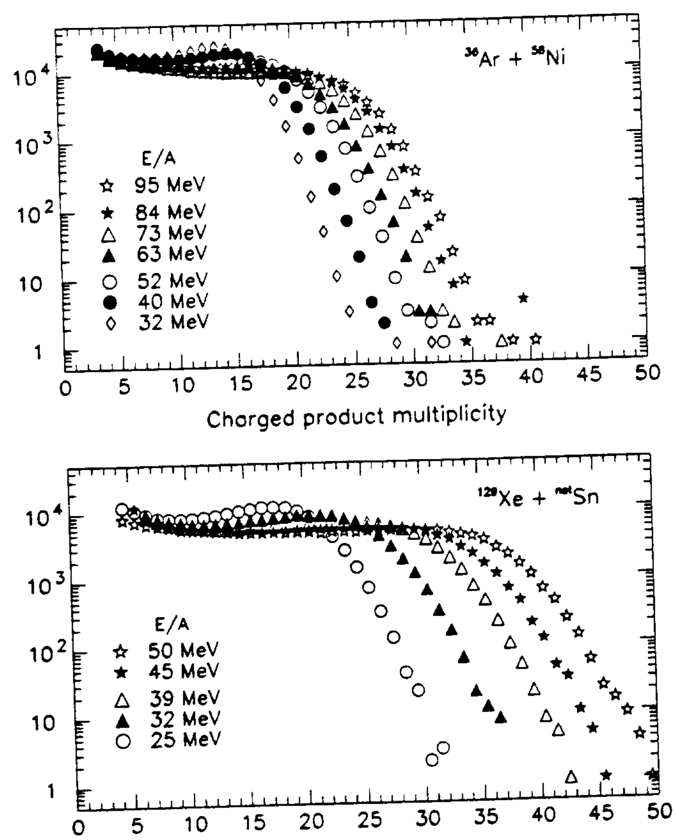

Fig. 1 : Total multiplicity of charged products as a function of the bombarding energy : for the ^{36}Ar + ^{58}Ni system (top), for the ^{129}Xe + ^{nat}Sn (bottom).

Dedicated detectors (75 µm thick Si and 2 mm thick Si-Li) provided the energy calibration of fragments stopping in the CsI scintillators at angles larger than 45 degrees. The energy calibration of the ionization chambers was carried out using alphas emitted by radioactive sources . For the forward ionization chambers, coupled with Si detectors, their energy calibration was also deduced from the calibration of Si detectors.

In addition to the energy calibration, a permanent checking of the stability of the electronics and detectors is needed. This is achieved by employing an electronic pulser system for the ionization chambers and Si detectors, and a laser pulser system for the plastic phoswiches and CsI scintillators.

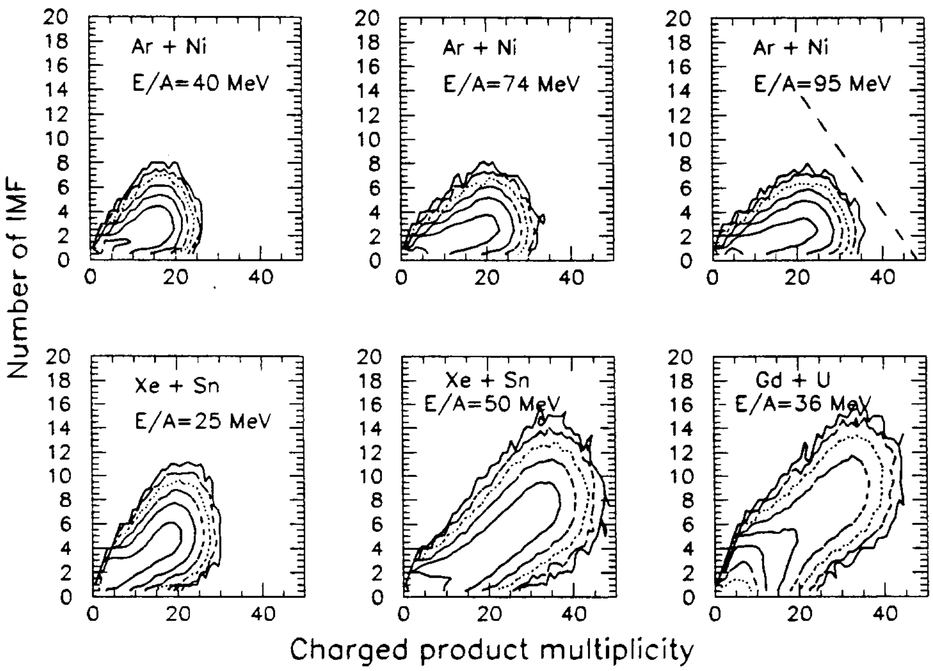

Fig. 2 : Correlation between the IMF (Z ≥ 3) multiplicity and the total multiplicity of charged fragments as a function of the bombarding energy : for the ^{36}Ar + ^{58}Ni system (top), for the ^{129}Xe + ^{nat}Sn and ^{155}Gd + ^{nat}U systems (bottom).

4. Preliminary data

The first experiments performed with INDRA in March and April 1993 have measured the following reactions :

^{36}Ar + KCl	E = 32, 40, 52, 74 MeV/nucleon
^{36}Ar + ^{58}Ni	E = 32, 40, 52 , 63, 74, 84, 95 MeV/nucleon
^{129}Xe + ^{nat}Sn	E = 25, 32, 39, 45, 50 MeV/nucleon
^{155}Gd + U	E = 36 MeV/nucleon

Eliminating neutron and gamma contributions from the raw experimental spectra, we can have access to the number of charged products measured in each event. The distribution of the total multiplicity of charged products as a function of the bombarding energy is plotted in fig. 1 for two systems, a light system, Ar + Ni, and a medium mass system, Xe + Sn. These distributions exhibit a well-known shape, a strong component at low multiplicity associated with peripheral collisions, and a broad component at high multiplicity associated with more central collisions. Both the width and the mean value of the broad component increase regularly with the bombarding energy. Similarly, the exponential tail of the multiplicity distributions evolves towards higher multiplicities when the bombarding energy increases. The continuous shift of the exponential tail with the bombarding energy clearly shows that there is no saturation of the experimental device.

The multiplicities observed in the Ar + Ni reactions reach high values compared with the total charge of the system ($Z_{TOT} = 46$). Multiplicity values of the order of 30 correspond to events in which half of the charged products have an atomic number Z = 1 and the other half, an atomic number Z = 2. Therefore, a complete disassembly of the projectile and the target is observed for these events.

In fig. 2, the number of intermediate mass fragments (IMF) is shown versus the total multiplicity of charged products. For this, a rough separation has been performed between light charged particles (LCP, Z = 1 and 2) and IMF's (Z ≥ 3). The spectra shown in fig. 2 will have to be confirmed after completion of the full Z identification. Three systems are displayed. The general trend is an increase of the number of IMF's when the total number of charged products increases. More and more fragments (LCP and IMF) are produced when the collision becomes more and more violent. However, different behaviours are observed, depending on the system considered. In the light system Ar + Ni, the number of IMF's does not evolve when going from the low energy to the high energy, while the total multiplicity increases continuously. As already observed on the close system Zn + Ti measured at various bombarding energies [39], this experimental fact could imply a decrease of the mean fragment size as the bombarding energy increases. On the other hand, the number of IMF's measured in the heavier system Xe + Sn strongly rises when going from 25 up to 50 MeV/nucleon. The trends exhibited in the heaviest system Gd + U are similar to that observed in the 50 MeV/nucleon Xe + Sn reaction. However, a contamination due to the carbon backing of the target is present at multiplicities lower than 10. The corresponding events will be removed in the subsequent analysis.

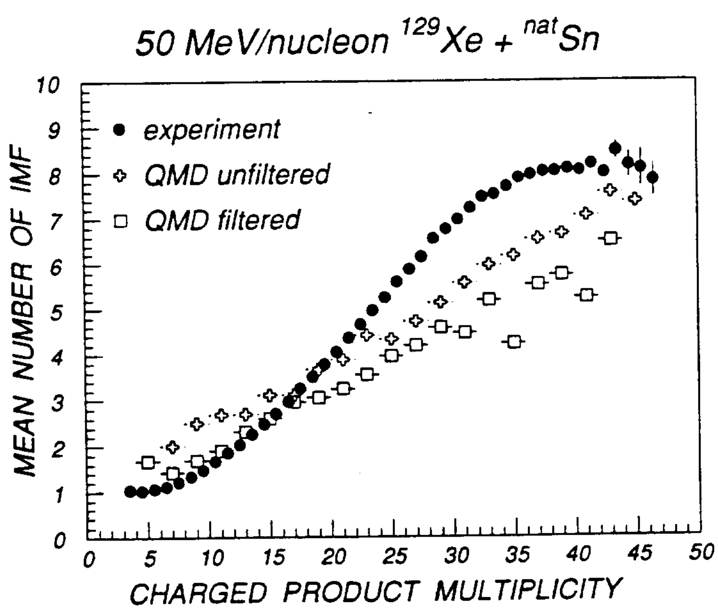

Fig. 3 : Correlation between the mean IMF (Z ≥ 3) multiplicity and the total multiplicity of charged fragments for the $^{129}Xe + ^{nat}Sn$ reaction at 50MeV/nucleon : experimental data (full circles), QMD calculations (open crosses) and filtered QMD calculations (open squares).

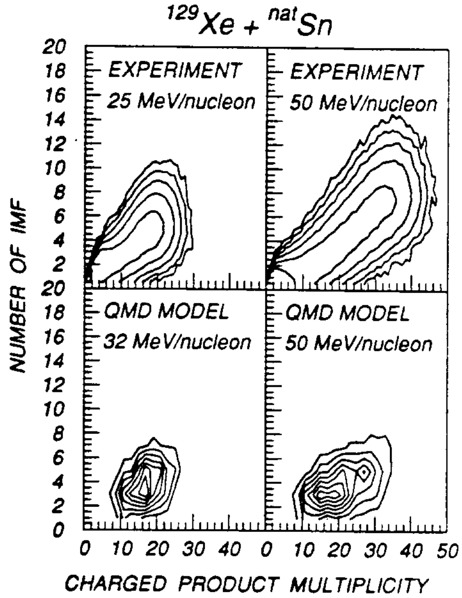

Fig. 4 : Correlation between the number of IMF's (Z ≥ 3) and the total multiplicity of charged products for the ^{129}Xe + ^{nat}Sn reactions at 25 (32) and 50 MeV/nucleon : (top) experimental data, (bottom) QMD calculations.

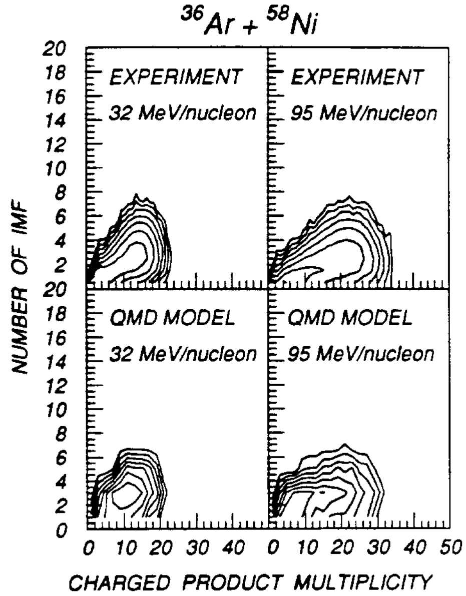

Fig. 5 : Correlation between the number of IMF's (Z ≥ 3) and the total multiplicity of charged products for the ^{36}Ar + ^{58}Ni reactions at 32 and 95 MeV/nucleon : (top) experimental data, (bottom) QMD calculations.

5. Comparison with QMD calculations

The quantum-molecular-dynamics (QMD) model [23, 40] is a n-body theory which simulates heavy-ion collisions at intermediate energies. The nucleons are represented by gaussian wave functions in momentum and coordinate space and interact via a mean field replaced by two and three body interactions, as well as via two body collisions. A soft equation of state has been used. The time evolution of the collision is followed till 200 fm/c. At that time, the cluster formation occurs : all nucleons being closer than 3 fm from each other in the coordinate space are considered members of the same cluster. After, cluster formation is completed, all clusters are practically cold nuclei.

In fig. 3, the QMD predictions are compared with the data of the 50 MeV/nucleon Xe + Sn reaction. The open crosses correspond to QMD calculations as described above. The open squares are simulated events filtered through the detector, taking into account geometrical acceptance, energy thresholds and multiple hits. The experimental data (full circles) are correctly reproduced at low total multiplicity of charged products. On the other hand, IMF (Z ≥ 3) multiplicities are underpredicted by more than 50 - 60 % for total multiplicities higher than 20. Such a discrepancy has already been observed at beam energies of 600 MeV/nucleon [41].

The number of IMF's (N_{IMF}) versus the total multiplicity of charged products (N_C) is plotted in fig. 4 for the Xe + Sn reactions at bombarding energies of 25 and 50 MeV/nucleon, respectively. Both the number of IMF's and the total multiplicity increases when the bombarding energy increases. However, as noted previously, QMD calculations only reproduce the data in a qualitative way. The total multiplicity of charged products is seen to increase with the bombarding energy. On the other hand, the strong increase of the number of IMF's when going from 25 to 50 MeV/nucleon is not properly reproduced, only an almost constant number of IMF's is calculated. This may be a hint for a too small energy transfer during the collision : not enough excitation energy is imparted to the fragments, leading to a lower emission of IMF's as compared with the experiment.

Similar comparisons are presented in fig. 5 for the light system Ar + Ni at 32 and 95 MeV/nucleon. In this figure, experimental data are confronted with the simulated events filtered by the detector. Both the approximate constant behaviour of N_{IMF} and the continuous increase of N_C as the bombarding energy increases is well reproduced. The last picture (fig. 6) shows the correlation between the mean number of IMF's and the total multiplicity of charged products. A quite good agreement is observed at the two bombarding energies between experiment and filtered calculations. Both data and calculations exhibit a slight decrease of the mean number of IMF's when the bombarding energy increases. In the Ar + Ni reaction at 95 MeV/nucleon, it should be noted that N_{IMF} reaches a maximum and even decreases at the highest multiplicities of charged products.

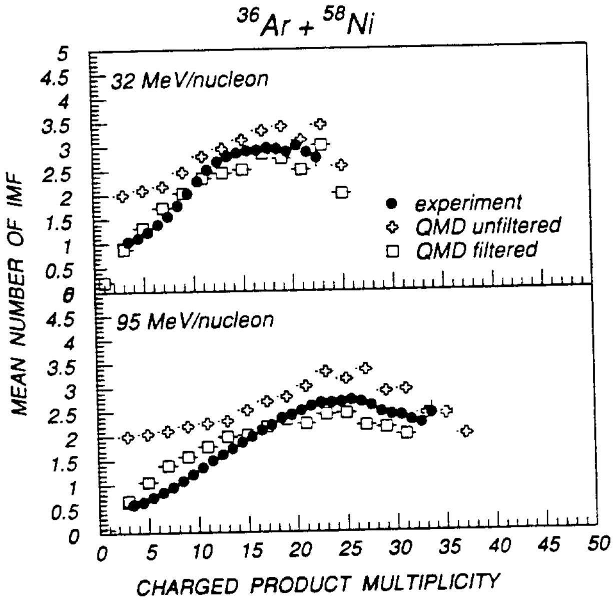

Fig. 6 : Correlation between the mean IMF ($Z \geq 3$) multiplicity and the total multiplicity of charged products for the ^{36}Ar + ^{58}Ni reactions at 32 and 95 MeV/nucleon : experimental data (full circles), QMD calculations (open crosses) and filtered calculations (open squares).

6. Conclusions

In this contribution, the physics program and the characteristics of the powerful 4π INDRA detector have been reviewed. Preliminary results on the total multiplicity of charged products as well as on the correlation between the number of IMF's and the total multiplicity of charged products have been presented. The data have been compared with the predictions of QMD model. Surprisingly, the calculations reproduce very well the experimental data obtained in the measurement of the light system Ar + Ni, whereas they fail in reproducing the experimental trends observed on the heavier system Xe + Sn. A comparison carried out between QMD and statistical models has already demonstrated that both classes of models led to similar decay properties of excited nuclei [42]. The obvious discrepancy between data and calculations could be due to a too low energy deposit in the system in the course of the collision, pointing out to a strong modification of the σ_{NN} cross section in nuclear medium.

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