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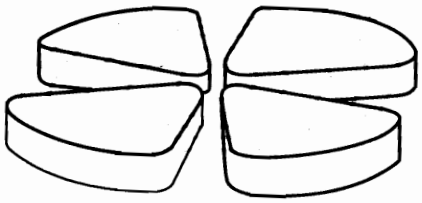

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Isospin Effects on Nuclear Dynamics and Thermodynamics.

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Isospin Effects on Nuclear Dynamics and Thermodynamics.

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In this paper we present a review of selected aspects of the nuclear dynamics and thermodynamics related to the Isospin.

1. INTRODUCTION

The isospin is first a symmetry. As a symmetry, it brings quantum numbers, selections rules and "geometrical" relations in the associated representations. Since it is violated by Coulomb term in the interaction, the symmetry is broken. On the other hand, its projection being the proton over neutron ration, the isospin is a degree of freedom in nuclear reactions. As a degree of freedom, it influences the nuclear properties. The effective nuclear forces have a non trivial dependence on isospin and the nuclear structure and cohesion vary with isospin. The nuclear equation of state is explicitly dependent upon the proton neutron ratio strongly. This dependence influence the neutron stars evolution and structure. Finally, the isospin is an experimental observable which can probe or signals different processes. It provides a test of the stopping power and a clock for the equilibration. Neutron matter distillation occurs in a first order phase transition in neutron rich matter while spinodal decomposition proceeds via collective modes with mixed isospin. The isospin dynamics leaves scars which can be observed in isotopic yields. This paper will try to stress important actual issues in this broad subject (see also [5]).

2. N/Z EQUILIBRATION

2.1. Pre-equilibrium GDR emission

As a first illustration of the role of the isospin in nuclear reactions let us consider a typical fusion reaction involving two nuclei with different N over Z ratio[3]. Figure one presents the evolution of the dipole elongation (the distance between the proton and neutron center of mass) and the associated dipole moment (the relative motion of protons and neutrons) as predicted by a Time Dependent Hartree Fock (TDHF)[6] calculation[2]. The observed spiral and damped oscillations is typical of the giant dipole vibration (GDR). Therefore the N/Z asymmetry is restored through the action of the GDR. This GDR plays the role of an antenna so one expect to observe the associated electromagnetic emission.. This as been recently reported in several experiments [4,1] such as the one presented in figure 1[1] where one can see that the N/Z asymmetric fusion reaction emits more GDR photons than the symmetric one.

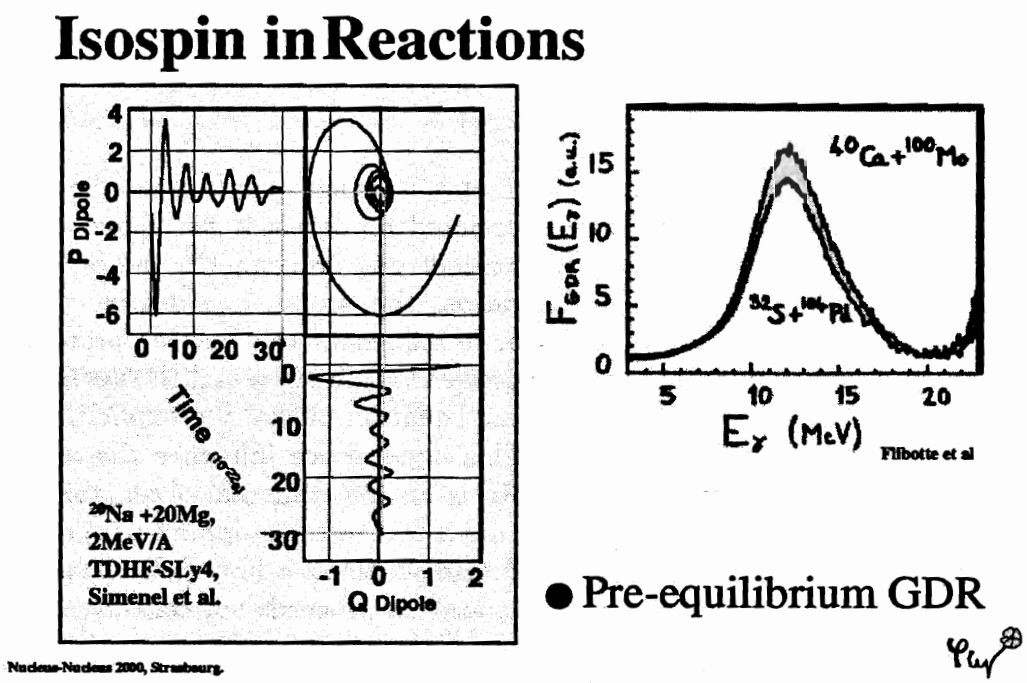


Figure 1. Left part the dipole elongation and associated dipole moment as a function of time and their correlation as predicted by a TDHF simulation [2]. Right part the experimental dipole strength observed for two reactions[1].

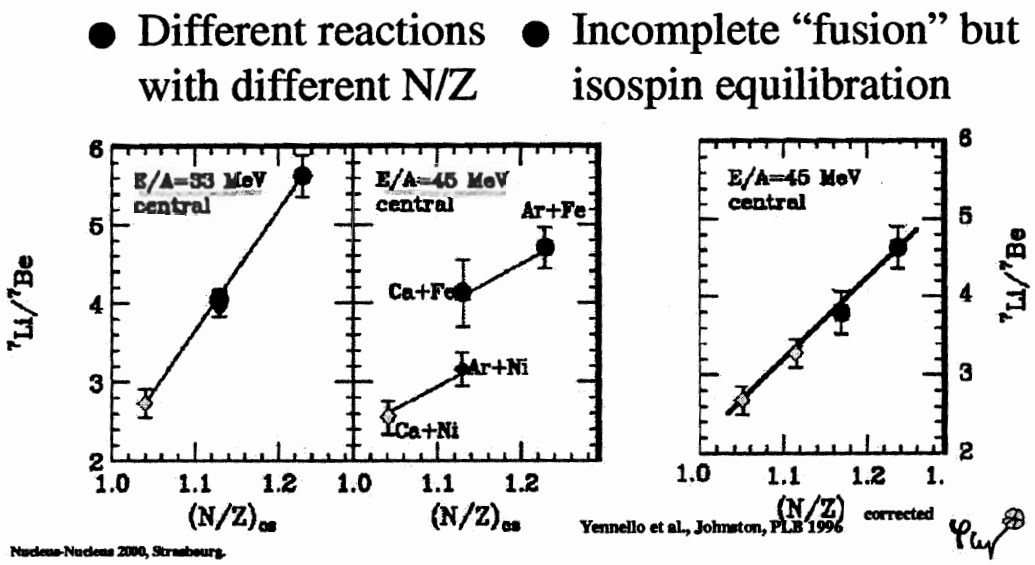


Figure 2. Isobaric ratio of miror nuclei with A=7 *as* a function of the coposite system N/Z (left) for to bombarding energies for four different reaction.In the right figure the composite N/Z have been fitted in order to reproduce the observed ratio (from [10]).

2.2. Test of entrance channel effects

The degree of equilibration of the N/Z entrance channel asymmetry have also been tested at higher energy [7–9]. Looking at isobar ratios as a function of the N/Z of the composite system one can see (Fig 2) that up to the Fermi energy an equilibrated source is formed. Indeed, different systems leading to the same composite nucleus exhibits the similar properties. At higher energy different entrance channel leads to different isotopic production. However, at moderate energy, the observed production is compatible with the creation of an equilibrated composite system through an incomplete fusion process depending upon the considered reaction.

2.3. Test of the nuclear stopping

In a recent study even more violent reactions have been studied in order to test the degree of stopping of matter in nuclear reactions. The figure 3 presents the global idea

(adapted from ref [11] : If we tag the particles coming from the projectile and the target using different N/Z we can infer the properties of the reaction and in particular the stopping power by looking at the isospin properties of the out going particles. If an equilibrated source is formed the N/Z of the produced fragment should be in-between the one of the target and the projectile. If the projectile is not completely stopped the forward particles should remember the original isospin of the projectile. Conversely, if the projectile bounce-back as in an hydrodynamical picture the projectile isospin characteristic should be found in the backward hemisphere.. The FOPI collaboration has recently investigated this point in the reaction involving A=96 isobars at 400MeV/A. They have compared four reactions: $Zr + Zr$ and $Ru + Ru$ which are used to calibrate the expected effect and the cross reaction $Ru + Zr$ and $Zr + Ru$ in order to study the stopping[12,13]. For example, they have proposed the proton differential multiplicity $m(y)$ as a function of the rapidity y as isospin tracer and the following ratio in order to follow the isospin mixing in the asymmetric reaction

$$R_Z = \frac{2m - m_{Zr} - m_{Ru}}{m_{Zr} - m_{Ru}} \tag{1}$$

This ratio is 1 for the $Zr + Zr$ reaction and -1 for the reaction $Ru + Ru$. For the intermediate reactions in case of a full equilibration the ratio is expected to be around zero independently of the rapidity bin considered while for some degree of transparency the ratio is expected to exhibit a strong velocity dependence. In case of a full transparency the ratio should be 1 in the velocity region of the initial Zr and -1 in the initial Ru direction. The results observed by the FOPI collaboration (fig 3) clearly show that at 400 MeV/A some transparency is present[12,13]. They have then been able to unfold the respective target and projectile contributions from the observed velocity distribution giving a quantitative estimate of the nuclear dissipation process.

3. ISOSPIN IN NUCLEAR PROPERTIES

3.1. Isospin dependent equation of state:

The isospin is not only an useful observable but is also an important nuclear degree of freedom. In particular even the most simple nuclear properties such as the biding energy, the density of the saturation point, and more generally the nuclear Equation of States (EOS) do depend upon the isospin content of the considered matter. This has been discussed by many authors (see for example [18,14,5,15]). Figure 5 illustrates this fact. The left part presents the nuclear matter energy as a function of the neutron and proton densities. The curves at N/Z constant presents a minimum (saturation point) up to a critical ratio. The right part shows that the isospin dependence of the saturation point is not known today, various models predicting different behaviors..

Our uncertainty about the isospin dependence of the EOS is also illustrated in figure 6. The left part shows the density dependence of the symmetry term (taken from ref. [19]). One can see that effective forces, Bruckner Hartree-Fock or Variational approaches leads to very different isospin term in the nuclear EOS. Stiff or soft isospin dependence have many consequences on the nuclear properties and dynamics (see for example [18]). This modifies the isospin dependence of the nuclear compressibility. This can be tested in heavy ion reaction considering for example the flow angle and in particular the so-called

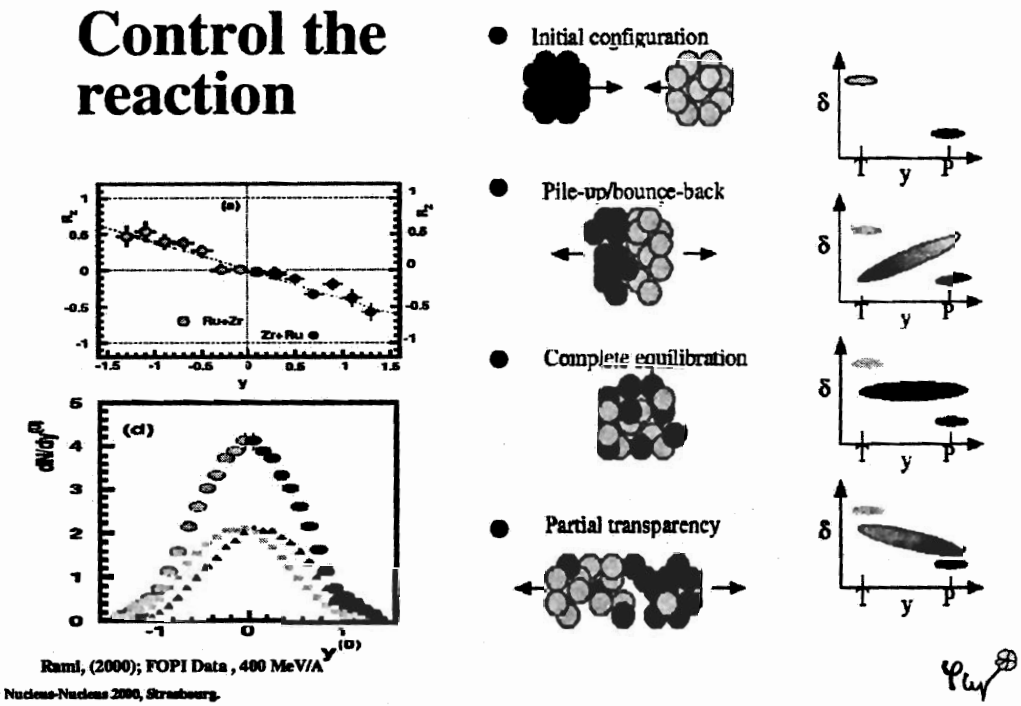


Figure 3. On the left schematic pictures from various nuclear processes with nucleon tagged by the isospin content of the projectile and target nuclei. The expected rapidity distribution of the isospin content of the reaction products is also plotted addapted from ref. [11]. Right part (top) the rapidity distribution of the ratio R_Z (see text) and (bottom) the resulting deconvolution of the respective contributions from the target and projectile [12,13]. Since only the forward emisphere was measured in FOPI the forward data of the $Ru + Zr$ data has been plotted in the negative rapidity region in order to represent the bacward emision of the reverse reaction.

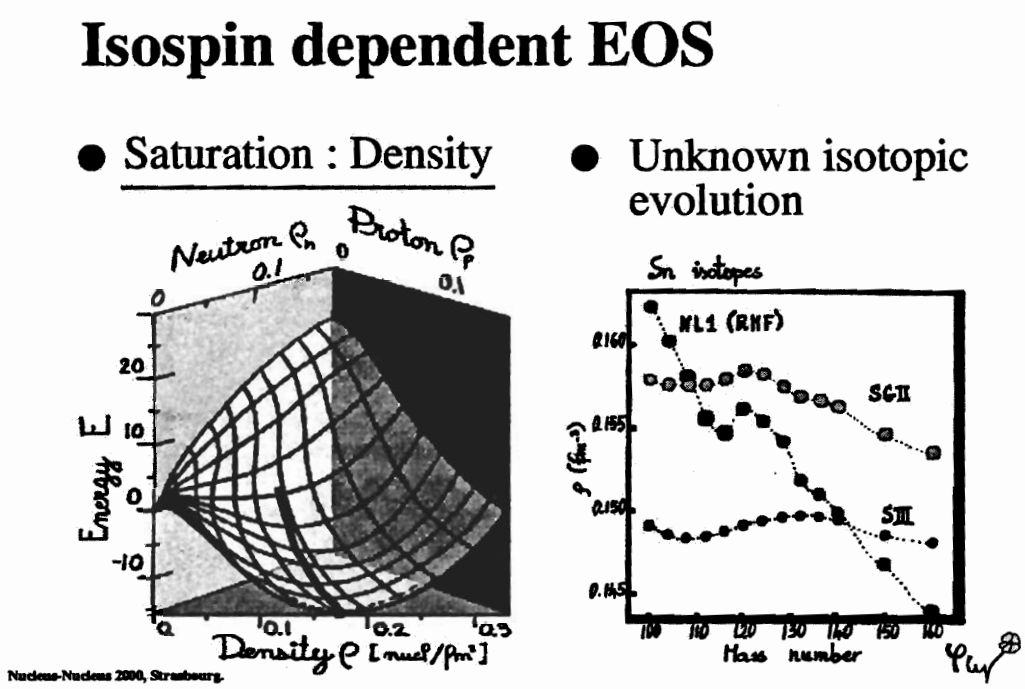


Figure 4. Left part the nuclear matter energy as a function of the neutron and proton density as predicted by the Hartree Fock (HF) theory with the SIII Skyrme interaction.Right part prediction of the central density in the Sn isotopes as predicted by various theory HF with SGII and SIII forces and a relativistic HF approach with the NL1 (addapted from refs [16,15]).

balance energy for which the mean field attraction and the collisional repulsion balance each other. This is shown in the left part of figure 6 where predictions are compared with the experimental observation of the balance energy as a function of the impact parameter [17]. In order to stress the role of the isospin two isobaric systems have been studied $Fe + Fe$ and $Ni + Ni$. The presented data seems to favor an stiff density dependence of the asymmetry term.

3.2. Isospin dependent density of state:

We have discussed the importance of the isospin degree of freedom on the nuclear properties at zero temperature. This importance appears even stronger when one studies the temperature dependence of the nuclear properties. The simplest observable containing information about the temperature dependence is the evaporation. Fitting the evaporation spectra with statistical models one can easily extract the level density parameter which relates the nuclear temperature to the excitation energy. This is a direct measure of the nuclear entropy or level density. Figure 7 presents a calculation based on a Hartree Fock Bogoliubov performed by Stephane HILAIRE for different Ni isotopes [22]. One can see that the most important features are the shell effect. Indeed, magic nuclei exhibit a strong reduction of their level density. It is important to not that even at 50 MeV excitation energy the shell effects are not yet completely suppressed.

3.3. Role of isospin on the States of nuclear matter

If we continue to explore the nuclear properties as a function of the temperature we can observe other phenomena. As far as the infinite nuclear matter is concerned Müller and Serot have recently stressed that since we are looking at a two fluid system because of the presence of neutrons and protons we should consider a three dimensional phase diagram[16] (see fig 8). In particular, if we expect a critical temperature about 17 MeV for symmetric nuclear matter this drops to zero at a critical N/Z ratio. Above this N/Z the (neutron) matter is not self bound anymore.

In finite systems the discussion is more complex both because of the small number of constituents but also because we cannot neglect the long range Coulomb force. The limit of existence of a charged nuclear drop in equilibrium with a gas have been investigated within the Hartree-Fock approach with Skyrme forces in ref. [20].It has been demonstrated that the Coulomb force plays an essential role and that the associated limiting temperature strongly vary as a function of the nucleus N/Z.

3.4. Thermodynamics

Recently many progresses have been performed in order to extract the nuclear thermodynamics from experimental data[25]. Vaporization threshold have been measure by the INDRA collaboration. Among the most famous attempts is the ALADIN caloric curve shown which resembles the one observed for a first order phase transition [23,24]. More recently the possibility to signal this transition using the fluctuation of the energy partition have been investigated and the presence of a negative heat capacity have been reported [32,31,28,30,26,29]. Examples are given in figure 9. The important point to notice is that now the study of the nuclear phase transition is becoming quantitative.

Since we are dealing with a liquid gas phase transition in a two fluid system one also expects the presence of a distillation (or fractionation) of the isospin asymmetric nuclear

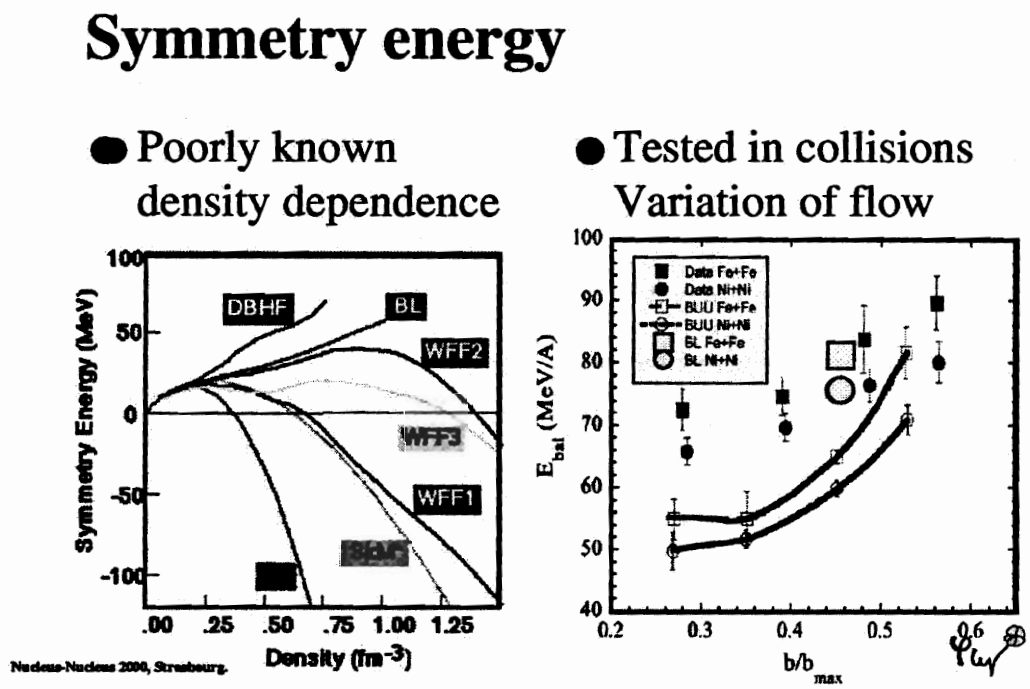
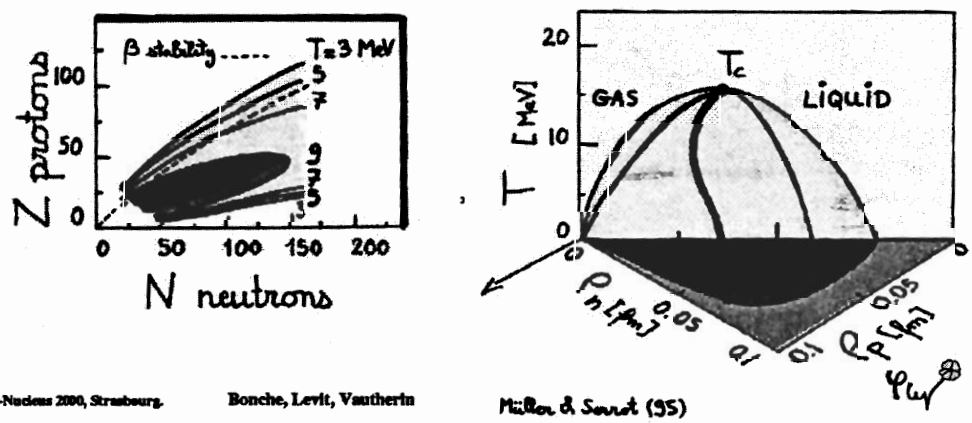


Figure 5. Left part the density dependence of the asymetry term for various models (addapted from ref. [19]). Right part the balance energy as computed from semi-classical approaches with a soft density dependence of the asymetry term (line) and for a stiff isospin dependence (big symbols) compaered with the experimental data (from ref. Pa97). Two isobaric systems are presented $Fe + Fe$ squares and $Ni + Ni$ circles.

Stability of nuclear drops

- Magnified by Coulomb
- Equation of states



Nucleus-Nucleus 2000, Strasbourg. Bonche, Levit, Vautherin Müller & Serot (95)

Figure 6. Left part: the N and Z dependence of the limiting temperature. Because of the Coulomb replusion the proton rich nuclei sustend only limited temperatures (from [20,21]). Right part the three dimensional phase diagram showing the coexistence line as a functuin of both the proton and neutron densities (from [16]).

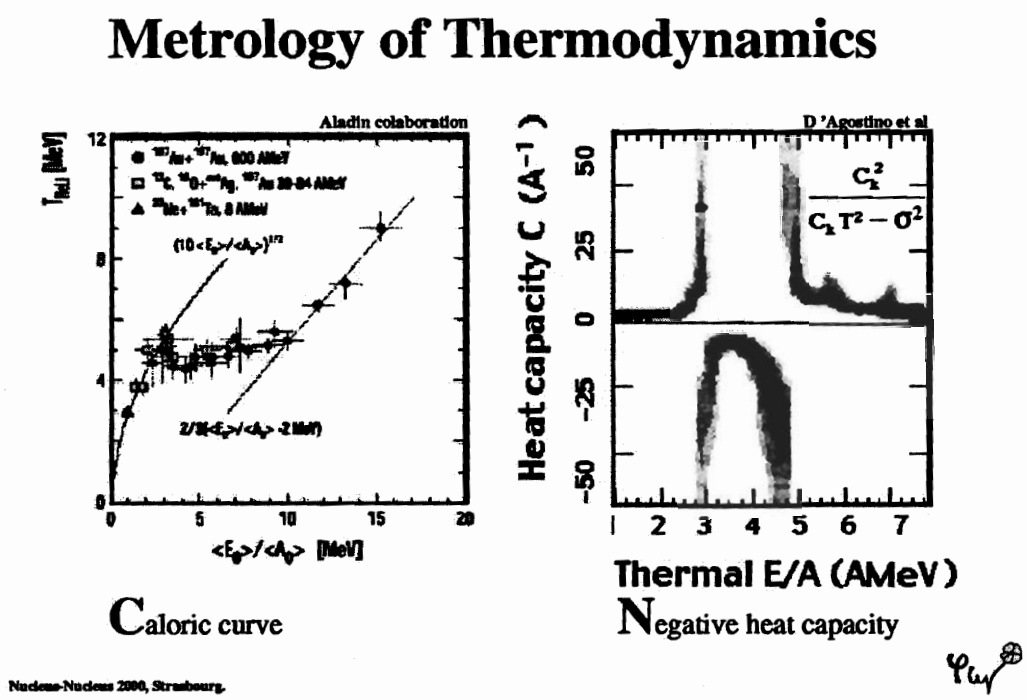


Figure 7. Left the caloric curve reported by the ALADIN collaboration[23,24]. Right the microcanonical heat capacity extracted from the kinetic energy fluctuations by the MULTICS collaboration[25,29].

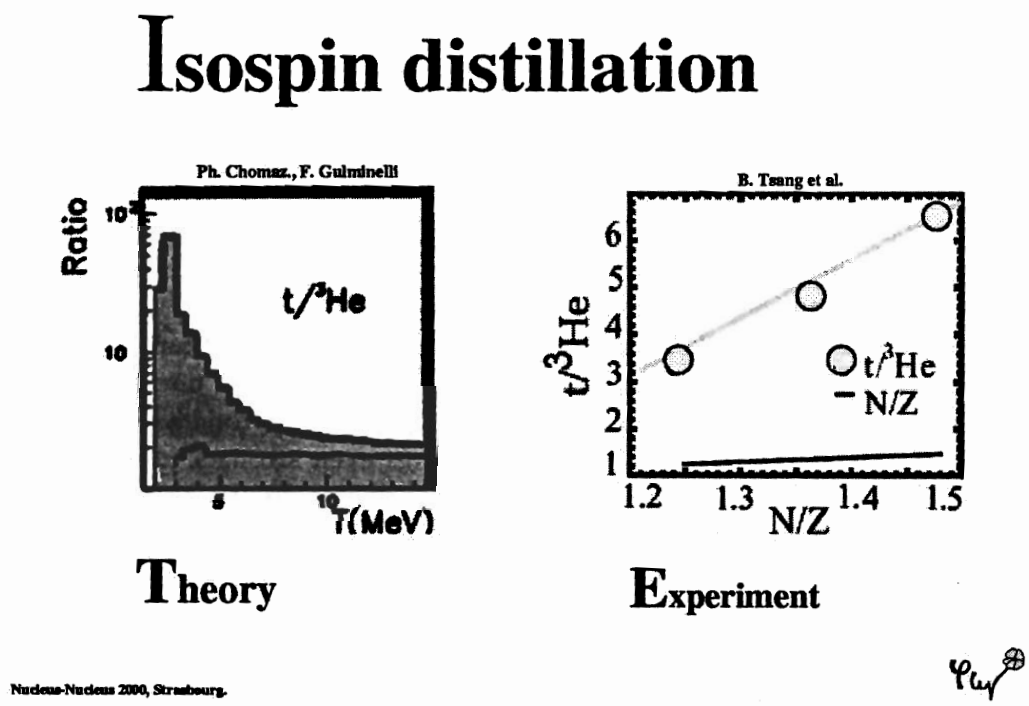


Figure 8. Left part t/He isotopic ratio calculated for an asymetric matter at various temperature [27]; right part experimental ratio as a function of the source asymetry [33]

matter. This was stressed first in ref. [16] and then illustrated in isospin dependent lattice-gas model [27]. This result is shown in figure 10 together with the first experimental results going in this direction ie showing a strong neutron enrichment of the gas phase (light fragments)[33].

3.5. Dynamics of a phase transition

This observation fits also well with the expected behavior of a dynamical symmetry breaking. Indeed, it seems now very probable that the observed phase transition occurs very rapidly through a spinodal decomposition. This interpretation based on stochastic mean field approach (see figure 10) has been now comforted by many experimental observation [25] Recently many progresses have been performed in order to extract the nuclear thermodynamics from experimental data[25]. Figure 10 also presents an example of comparison between the theory and the experiment [34,?, ?]. During the spinodal un-

stabilities protons and neutrons do not flow the same way as shown in the last figure of figure 10 from [18]. After fragmentation the isospin content of the matter changes with its density, low density regions becomes neutron rich while high density phase tries to reach a symmetric matter.

4. Conclusions

In this talk we have shown on few examples the possible roles of the isospin in nuclear dynamics and thermodynamics. The isospin can be a useful tool to investigate the dynamics or to control the thermodynamics. The N/Z equilibration or the isospin distillation are possible observables which can bring light on fundamental problems in nuclear physics. But the role of isospin is much more than a new observable. It is a basic degree of freedom and symmetry of the subatomic world. The forces are isospin depend and the nuclear fields carry isospin quantum numbers. Therefore all the nuclear properties are expected to be isospin dependent. This reinforced by the Coulomb electromagnetic interaction which break the isospin symmetry and brings even stronger effects. The nuclear binding, the saturation point, the level density and the whole phase diagram are isospin dependent. The availability of new isospin factories as well as the amazing progress of the nuclear models make us very optimistic about the fast development of the field of research discussed in this paper.

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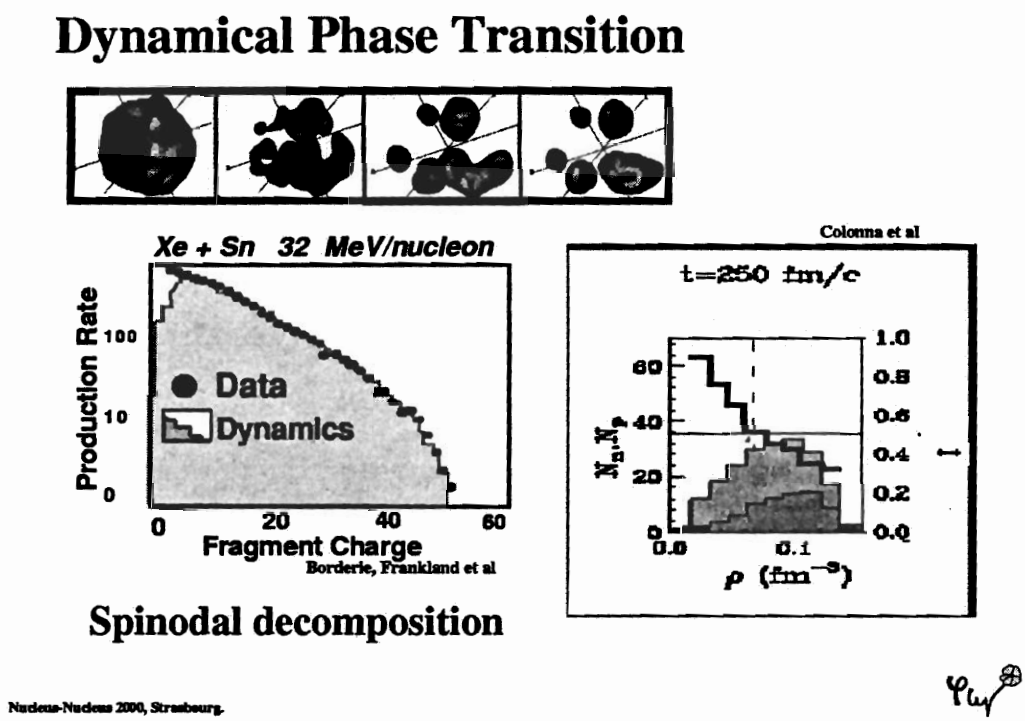

Figure 9. Left part comparison of the INDRA data for the multifragmentation in Xe+Sn at 32 MeV/nuclon central events with the stochastic mean field prediction for a spinodal decomposition [34]; top typical dynamical simulation of a spinodal decomposition [35]; right part final spinodal decomposition of an asymetric matter as a function of the local density are shown the I=(N-Z)/A right scale and the neutron and proton number sitting in such a density region (addapted from ref [18])

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