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Introduction

"Complexity" has become so fashionable that there exists now a fullfledged journal dedicated to this quite legitimate science [1] . The bonuses expected from fundamental research on "complexity" cover items as diverse as weather prediction, stabilization of stock markets, several branches of biology, etc. One now begins to discover the fascinating richness of self-organization in apparently disordered systems and the immense wealth of *moderately* broken symmetries emerging from large collections of individually simple systems.

The nucleus is a mandatory step in the understanding of nature, between elementary particles and atoms and molecules. To what extent might it be understood with the help of complexity viewpoints? Conversely, could the atomic nucleus provide a laboratory for understanding the behavior of "complex" systems? The purpose of this note is to capitalize on the fad for complexity and claim that nuclear physics is an excellent choice to do physics of complex systems ...without getting lost.

Nuclei as sets of interacting nucleons

We shall focus on "traditional" nuclear systems, where only protons and neutrons, and a few photons and mesons are present. This choice is not fully arbitrary. The most microscopic constituents of nuclei are presumably the quarks and virtual gluons, which nucleons and mesons are made of. One could hence consider that they better correspond to what one would call elementary constituents of the system. But it turns out these quarks and gluons are basically and tightly bound in intermediate structures, mainly the nucleons. In that sense nucleons are the effective elementary bricks which constitute "normal" nuclei. In order to "see" a signature of the presence of quarks one has to excite nuclear matter so much that actual nuclei do not exist anymore. Such exceptional thermodynamical conditions may have indeed occured during the early stages of the universe, but present day nuclei may safely be viewed as collections of interacting nucleons.

Nuclei do interpolate between systems with few degrees of freedom ($N = 3$ for instance) and Avogadro-size ($N \sim 10^{23}$) systems. As a matter of fact, the richness of phenomena shown by nuclei when N runs from a few units to a few hundreds is staggering : twenty or thirty years ago, the beauties of the shell model [2] or the collective model [3], as efficient simplifications of this many-body problem, were just one example of what "hard" science can do to make the real world intelligible to our frail humain brain. More recently, it has been found that order parameters are still useful when very excited states are studied: see the discovery of superdeformations [4] , and of new kinds of giant resonances [5] .

Complex nuclear systems

As stated above the purpose of this note is to draw the attention of the reader on the complexity of nuclear dynamics. For this purpose we shall briefly introduce our point by having a short look backwards, into the early days of nuclear physics. We shall see that a stochastic picture of nucleonic motion inside the nucleus is almost as old as nuclear physics itself. In spite of the symmetries of the mean field in which nucleons move, this stochastic picture remains basically valid and reflects the complex nature of nuclear dynamics. During the eighties, experiments performed at the new heavy ion facilities all over the world have shown that this complex picture is in fact a law rather than an exception. We shall present a few contemporary examples exhibiting such typical features in heavy ion reactions. These examples, being "contemporary" also raise widely open questions and thus constitute a lively body of researches. Moreover the techniques used to approach this kind of problems are of much more general interest than just nuclear physics. From an experimental point of view , physicists have learned to build detectors able to accomodate tens, hundreds, even thousands of ejectiles. Moreover, they have gained experience in analysing such bodies of data and extracting from them some relevant physical information. On the other hand, the theoretical description of these complex heavy ion reactions requires the development and the simulations of microscopic, dynamical models in strongly out of equilibrium situations. We shall try to describe some benchmarks for such present and future tasks.

Bohr and Kramers : early stochastic pictures

It is probably Niels Bohr who, in his article in "Nature" in 1936 [6] , introduced for the first time a statistical concept in the description of a nuclear problem, namely the interaction of a neutron with a target nucleus. Such a statistical picture of the numerous interactions of the incident neutron with the nucleons constituting the nucleus basically reflects the complexity of the process In the case of moderately energetic neutrons, such as those available in the mid-thirties, the whole interaction process is very long in terms of nuclear times, and leads to the formation of an excited nucleus whose subsequent decay may be safely described by a statistical assumption.

At the turn of the same decade, Kramers, in a cornerstone paper [7] on the Langevin description of chemical reactions, also suggested that the newly discovered fission phenomenon might possibly be viewed as a diffusion process of a collective variable, such as the deformation of the nucleus, over a potential barrier. Again the description of a nuclear process implied the underlying assumption of complicated nucleonic motion, which as a first step was treated as a heat bath with respect to the deformation considered as a Brownian particle. Again complexity underlied the phenomenological, gross description of the physical situation.

Mayer, Jensen and Wigner : the beauties of the shell model

But apparent regularity was also a feature of nucleonic motion. Indeed the introduction of the shell model in the late forties by Mayer and Jensen shed a new light on the motion of nucleons inside a nucleus [2]. With a good approximation, nucleonic motion could be represented as nucleons following single particle trajectories related to the levels of a unique, common, one-body potential. The shells (degeneracies with energy gaps between them) can be understood as corresponding to classical closed orbits in the potential, and thereby be related to its symmetry properties [8]. Incidentally, this concept is also well applicable to another finite fermion system. microclusters, where it is further developed into the existence of "supershells" due to an interference between two nearby orbits [9] . All told, the shell model picture suggested regularity rather than complexity, hence a picture apparently difficult to reconcile with the previous stochastic one.

In fact the paradox had a short life as Wigner soon realized [10] that the very structure of nuclear spectra was much richer than a simple textbook exercice of quantum mechanics. By studying spacings of compound nucleus levels he showed that the distribution of spacings was special, and a signature of a restricted class of stochastic hamiltonians. As a side product his remark gave birth to the today most commonly admitted definition of quantum chaos!

Spectra of compound nucleus levels do provide the best experimental data for statistical studies of quantum chaos [11] . Again nucleonic motion was associated to stochasticity, at least at high excitation energy, thus reflecting the complex nature of nuclei.

"Modern" nuclear complexity : the physics of violent collisions

The beauties of the nuclear shell model enlightened the nuclear physics of the sixties and seventies and allowed the development of original contributions to the physics of strongly interacting many-body systems. The Hartree-Fock mean field theory allowed the description of many ground state nuclear properties. with the help of realistic phenomenological effective interactions. The dynamical version of this theory, "Time Dependent Hartree-Fock" (TDHF), however soon suffered from deficiencies in the description of nuclear collisions at increasing bombarding energies. Basically the mean field picture was unable to account for the dissipation responsible for the heating of nuclei, such as Bohr had picturized it, and such as experimentalists were starting to observe it in fusion-like reactions of heavy ions at beam energies of a few tens of MeV per nucleon. Again, statistical concepts came back through thermodynamical preoccupations, such as the determination of the nuclear matter equation of state. This obliged nuclear physicists to depart from a mean field picture and to accomodate the dissipative patterns experimentally observed. The existence of so called nuclear temperatures also implied the occurence of corresponding thermal fluctuations and brought back the nuclear physics community to basic questions of statistical mechanics of complex systems. Moreover it rapidly turned out that many of the properties of atomic nuclei, such as the nuclear equation of state or transport properties, could in fact only be studied in strongly out of equilibrium processes. In turn, these strongly out of equilibrium situations exhibited original features calling for a specific understanding.

The dynamics of multifragmentation

The dynamics of nuclear fragmentation in heavy ion collisions is an example where a discussion of both the chaotic structures and the complexity due to multiparticle correlations may be most relevant. In heavy ion collisions, at beam velocities of order the average velocity of nucleons in a nucleus at rest, the formed system may break up into several intermediate mass nuclei (see Fig. 1). Physicists have been seeking for many years a signal of a liquid-gas phase transition of a finite system in such collisions. Whatever the underlying mechanism, its time scale mixes with the typical time scales of the system. It has thus to be understood in a dynamical sense and the road to a proper theoretical description of multifragmention was and remains snaky. The first step is to depart from the safe mean field picture to accomodate dissipative features. At the quantal level this is a very hard task which has not yet received a commonly accepted answer. Fortunately enough, the de Broglie wavelenghs of nucleons inside colliding heavy ions become very soon negligibly small with increasing bombarding energies. This allows to rely on semi-classical descriptions which gain in simplicity as compared to the quantal framework.

During the eighties a nuclear version of the Boltzmann equation was used with success in this context [13]. It turned out that although a complete theoretical justification of such an equation might still be missing, its application to actual heavy ion collisions helped a lot in the understanding of basic dynamical process. In particular, this allowed to explain with a reasonable degree of confidence the formation of hot compound systems. The dynamics of multifragment formation, however, could not be fully explained within such a theoretical framework, which by nature predicts only average quantities.

The next step in the development of these microscopic theories was to extend basic kinetic equations into a stochastic regime [14]. Actually, stochastic extensions of kinetic equations, introduced in the late fifties, had been studied during the sixties and seventies in situations close to equilibrium. They are now developed and applied in both a strongly out of equilibrium context and in a case where self-consistent mean field effects still play an important role. These descriptions are presently the object of many investigations. Combined with elaborate statistical descriptions of the decay properties of the formed fragments, they could provide a microscopic theory of multifragment emission.

The relevance of such research subjects is much wider than the only understanding of fragment formation. Indeed these dynamical systems offer interesting clues to the very general question of the quantum/classical correspondance. As mentioned above, variations of the beam energy amounts, in some sense, to tune an effective Planck constant. On the other hand the self-consistent nature of the nuclear mean field makes the basic equations of motion non linear, which brings us back to chaotic features. This non linearity seems to be unavoidable, as stemming from a reduction of the many-body problem to one-body dynamics.

From statistical to non statistical patterns

It is well known that the flow of a classical incompressible fluid, which for low viscosity behaves in a laminar way, exhibits highly chaotic and irregular behaviours for large viscosities. In this viscous regime the flow is both unstable and unpredictible and a small perturbation at a certain time may rapidly lead to a strong distortion of the flow pattern. An understanding of a large number of statistical properties of the fluid can then be obtained by fragmenting at different scales the turbulent structures, called "eddies", into smaller and smaller eddies. This random cascade process of fragmenting eddies provides a main physical mechanism in which the energy of the flow is transmitted to motion at smaller scales down to almost the molecular scale, where fragmentation is stopped by dissipation.

In heavy ion collisions one expects that hot, expanding nuclear matter may enter a region where finite length density perturbations become unstable [15] . Inside this region of mechanical instabilities, called spinodal instabilities, the system is thermodynamically unstable with respect to small wavelength fluctuations and it is doubtful that Boltzmann-like kinetic equations, which neglect high order correlations, continue to be valid approximations. Actually, the picture emerging from such studies resembles that of a critical phenomenon, out of equilibrium, for a random cascade of fragmentations with unstable blobs of nuclear matter at different scales [16] . For some specific scaling fragmentation functions of this non-equilibrium cascading process, the distribution of fragment sizes may reach a limit reminiscent of those distributions given by percolation [16] . This leads at once to the following questions: is the nuclear fragmentation process related to a critical phenomenon, and if so, what is the nature of this finite size phase transition, and under which kinematical conditions of the collision is the dynamics of the fragmenting matter governed by the criticality?

As yet, experiments with an exclusive analysis, event by event, of the fragment size distribution are restricted to nuclear emulsion techniques and only a limited number of fully resolved events are at our disposal. Nonetheless, such questions will soon be studied in great detail by electronic experimental techniques using sophisticated multidetector systems now operational at GANIL-Caen, GSI-Darmstadt and MSU-East Lansing. Existing data strongly suggest that indeed a critical phenomenon is involved. The way to exhibit it is by analyzing observable quantities which behave in a qualitatively different way when a critical phenomenon is present.

The next step is to compare these analyses with models, such as percolation or non-equilibrium random cascading, where the nature of the "finite size phase transition" is well understood. In Fig. 2 we show an example of such an analysis [17] for the dimensionless quantity $\gamma_2 = M_2 M_0 / {M_1}^2$ plotted versus the reduced multiplicity m of fragments for :

(i) the experimental data on fragmentation of gold nuclei with incident energies $E/A \simeq 1GeV$ in the nuclear emulsion (upper plot) ,

(ii) the three-dimensional random bond percolation on a cubic lattice (bottom plot) which in the infinite lattice exhibits a second-order phase transition when $m \longrightarrow 0.25$.

Fragment-size distribution is calculated in each event by the moments $M_k = \sum_Z Z^k n_Z$, where the sum runs over all fragment charges (sizes) excluding the largest one. The value $\gamma_2 >> 2$ indicates a power law distribution of the fragment sizes as expected around a critical point. As seen in fig. 2, both in the experimental data and in the three dimensional percolation , large values of γ_2 are found around $m \simeq 0.25$.

Concluding...

The theories of percolation and non-equilibrium random cascading for fragmentation, as well as the exclusive analysis of the multifragment events, helped to develop the idea that randomness and disorder associated with heavy ion collisions may result in spectacular clusterization features [17, 18] . The latter are not merely the result of statistical fluctuations of the otherwise perfectly smooth spectra of fragments. They also represent a genuine, physical effect related to the scaling features of the nuclear dynamics. In this case, one is naturally led to study the distributions, like the fractal ones, which satisfy the observed anomalous scaling laws and reflect the scale invariance of an underlying geometry or chaotic dynamics. This development leads to new types of kinetic theories and a new version of the statistical mechanics of small systems in strongly out of equilibrium situations, with the possibility of dynamical instabilities and spontaneous pattern formation. Let us risk a wild speculation: nothing prevents *a priori* a local density fluctuation in a soup of nucleons from propagating and even self replicating. It is a challenge to understand on a microscopic basis the dynamical evolution of these fluctuations. Stochastic extensions of kinetic equations might constitute a way to attack this fundamental problem.

There is probably a long way before all these problems can be correctly formulated and solved. But even at the present stage of this development it may be helpful to discuss the atomic nucleus as an intrinsically dynamical object. Its extended compact structure. the strength of quantal effects and the delicate balance of an infinite range Coulomb force and a short range nuclear force makes the atomic nucleus a unique and fascinating object in the research of "complexity". To make a long story short. both theoretical and experimental efforts are now helping to explain nuclear collisions where classical limits and residual quantum mechanisms compete, collective and isolated degrees of freedom coexist, with many cases of interferences, intermittencies, stability and unstability.

Naturally, a global mathematical and/or conceptual framework which could carry the experience gained in nuclear physics to other, more fashionable fields of "softer" science is still missing. Interdisciplinary experts are not so numerous, and there remains a long way until the time when solutions of a many-body problem in nuclear physics could turn out to be useful in biology, sociology or economy. Nonetheless, it can be safely claimed that atomic nuclei, and more specifically nuclear collisions, provide a benchmark for the study of complexity, unique by the richness of its phenomenology. It would be a serious mistake to overlook it.

References

[1] Journal of Complexity, ed. J.F.Traub, Columbia University, (N.Y.).

[2] O. Haxel, J.H.D. Jensen and H.E. Suess, Phys. Rev. **75** (1949) 1766; M.G. Mayer, Phys. Rev. **74** (1948) 235; ibid. **75** (1949) 1969.

[3] N. Bohr and F. Kalckar, Mat. Fys. Medd. Dan. Vid. Selsk. **14** (1937) no. 10; A. Bohr, Mat. Fys. Medd. Dan. Vid. Selsk. **26** (1952) no. 14; A. Bohr and B.R. Mottelson, Mat. Fys. Medd. Dan. Vid. Selsk. **27** (1953) no. 16.

[4] P.J. Twin et al. Phys. Rev. Lett. **57** (1986) 811.

[5] P.G. Hansen and B. Johnson. Europhys. Lett. **4** (1987) 409.

[6] N. Bohr . Nature **137** (1936) 344.

[7] H. A. Kramers, Physica **VII 4** (1940) 284.

[8] R. Balian and C. Bloch. Ann. Phys. (NY) **69** (1972) 76 and references therein.

[9] H. Nishioka, K. Hansen and B.R. Mottelson. Phys. Rev. **B42** (1990) 9377.

[10] E. P. Wigner, Ann. Math. **62** (1955) 548.

[11] O. Bohigas and H.A. Weidenmüller, Ann. Rev. Nucl. Part. Sci. **38** (1988) 421.

[12] B. Jakobsson, G. Jönsson, B. Lindkist and A. Oskarsson, Z. Physik **A307** (1982) 293.

[13] G. Bertsch and S. Das Gupta. Phys. Rep. **160** (1988) 189.

[14] S. Ayik and Ch. Grégoire. Phys. Lett. **B212** (1988) 269.

[15] H. Heiselberg, C.J. Pethick and D.G. Ravenhall , Phys. Rev. Lett. **61** (1988) 818.

[16] R. Botet and M. Ploszajczak, Phys. Rev. Lett. **69** (1992) 3696.

[17] X. Campi, J. Phys. A Math. Gen. **19** (1986) L917; Phys. Lett. **B208** (1988) 351.

[18] M. Ploszajczak and A. Tucholski, Phys. Rev. Lett. **65** (1990) 1539.

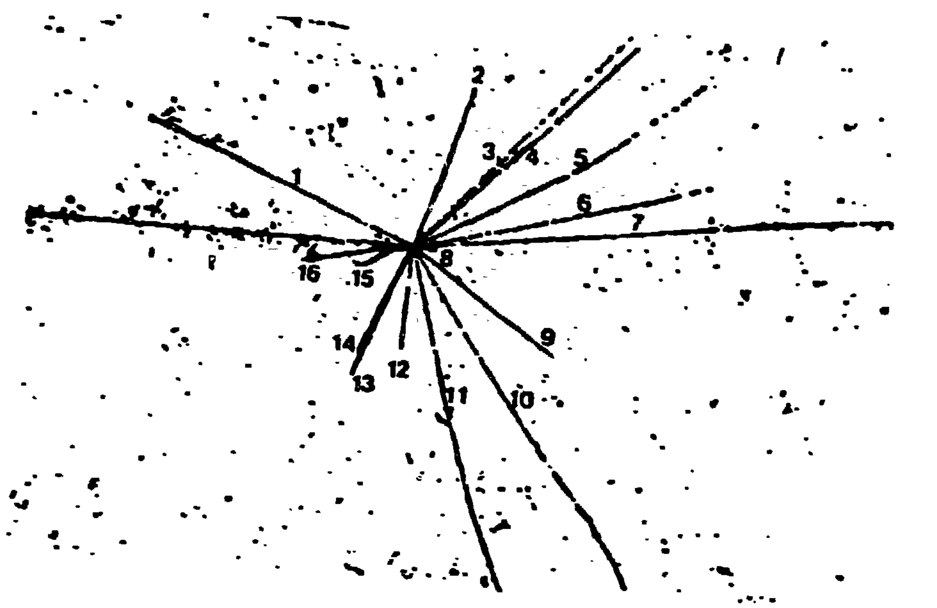
Figure captions

Fig. 1

The collision of carbon ion of 852 MeV in a nuclear emulsion. The charge $1 \leq Z \leq 4$ of 16 fragments has been identified. From [12].

Fig. 2

The dimensionless quantity γ_2 for the experimental data corresponding to the fragmentation of gold nuclei ($A = 197$) with the incident energy $E/A \simeq 1GeV$ in the nuclear emulsion (the upper plot) and in a three-dimensional random bond percolation on a cubic lattice (the bottom plot). The experimental data consists of about 400 events for which charges of all fragments have been measured. The percolation calculation has been done for the number of occupied sites equal to the number of nucleons in the fragmenting gold nucleus. For each percolation event separately , the bond activation parameter q has been chosen at random ($0 \leq q \leq 1$). For further details see the description in the text. From [17] .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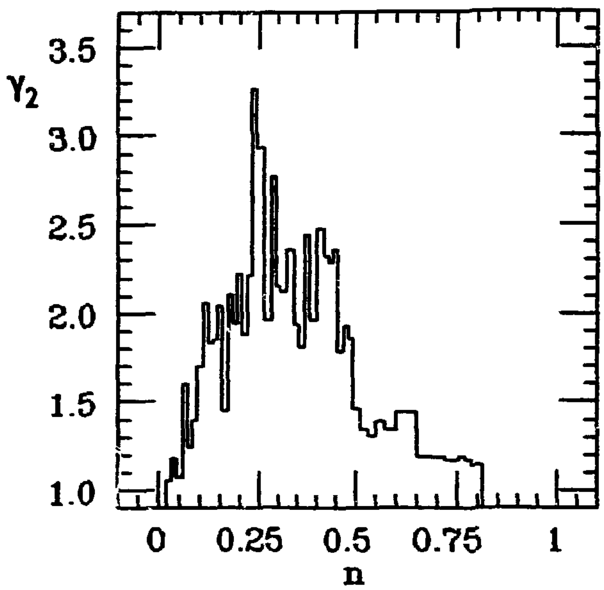

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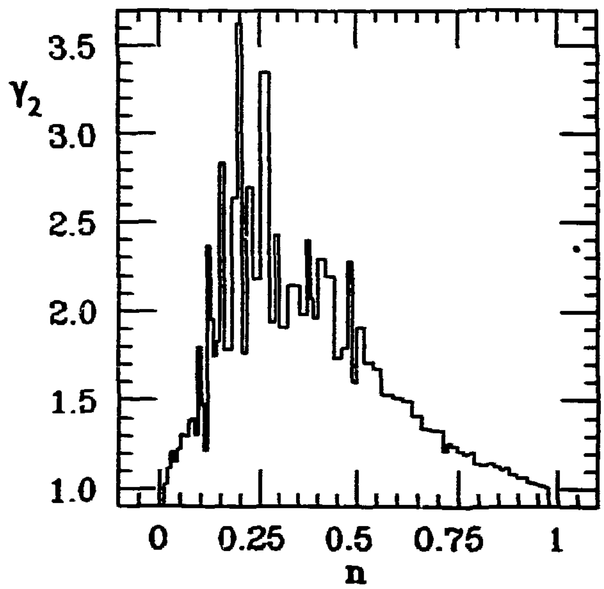

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