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PROSPECTIVES IN HEAVY ION NUCLEAR PHYSICS

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Abstract

The developments and the motivations of the heavy ion physics are briefly outlined. Special attention is paid to the attempts to determine the equation of state of the matter constituting the atomic nuclei, as well as the possibility of studying its various phases. Possible connections with other fields in physics are mentioned.

1. Introduction

Nuclear physics has entered the domain of heavy ions for about 25 years now. However, the main impulse was given in the beginning of the seventies with the installment of dedicated accelerators and this field has since taken a steadily increasing importance.

Since around 1930, the atomic nucleus was studied with the help of Van de Graaff and cyclotron accelerators when a target nucleus is bombarded with accelerated light particles like protons, or alpha particles (electrons were also used). Let us remind for the unaware reader the basic difficulty of nuclear structure experiments. In order to investigate the structure of a small body like a nucleus one needs a probe with a smaller wavelength, e.g. a proton with a sufficient velocity. Furthermore, a charged particle has to have a minimum energy to overcome the Coulomb barrier created by the charges inside the nucleus. One would be inclined to use more and more energetic particles but then one inevitably brings a greater and greater damage to the system. That is why for a long time (and for technological and economical reasons as well) one has restricted oneself to light particles of small and moderate energies, like protons with an energy of less than ~ 100 MeV (we remind that the binding of a nucleus is around 8 MeV per nucleon). Moreover, the analysis of the experiments was far from trivial. Because of the important disturbance, the response of the nucleus to these probes has a nontrivial connection with its structure. Nevertheless, a great wealth of information has been obtained in fifty years. Let us try to summarize the main points in the following dramatic shortcut, which, of course, cannot give proper credit to the extraordinary efforts of the numerous laboratories in the world :

1. the nucleus is a self-bound system of protons and neutrons (the nucleons). Its size is typically of a few fm (1 fm = 10^{-13} cm) ;

2. the nucleons inside the nucleus behave more or less independently. In a first crude approximation, the nucleus in its ground state ressembles a Fermi gas of nucleons travelling in an attractive meanfield (generated by themselves in a non really intuitive manner) ;

3. the nuclear forces, i.e. the force acting between two nucleons, is repulsive at short distances and attractive at long distances (its range however does not extend to more than, say, 1 fm). They are saturating, i.e. they are responsible for a roughly constant density of all nuclei. This feature is more easy to conceive intuitively ;

4. the binding energy of all known nuclei can be formulated in a rather compact form, known as the Bethe-Von Weiszäcker formula

$$B.E = a_v V - a_s S - E_{coul} - E_{as} \quad ,$$

where a_v , a_s are positive constants, V is the volume of the nucleus, S its surface and E_{coul} is the Coulomb energy due to the distribution of the charges. The last term E_{as} , the so-called asymmetry energy, is not very much important, except that it forces the nucleus to be composed of approximately equal numbers of protons and neutrons. The above formula has the same form as the one for the energy of a charged droplet of liquid, the surface term accounting for the surface tension. This suggests that the nuclei can be viewed as small samples of a liquid matter, named nuclear matter ;

5. the low lying excitations of a nucleus display a very rich pattern which arises from single-particle excitations and from collective (surface) vibrations, as well as from the interference of both. In this respect, the nucleus bears some ressemblance with liquid ^{3}He and also perhaps with an electron gas. The nuclei also have the property (at least for some of them) of showing rotation spectra.

Let us now come back to the heavy ions. For a nuclear physicist, a heavy ion is nothing but that a (relatively) heavy nucleus that is used to bombard a target. When injected in an accelerator, the nucleus is not (necessarily) stripped from all of its orbiting electrons, and that is why one refers to it as an ion. Nowadays, heavier and heavier ions are used at always higher and higher energies. The following question arises naturally : why to use heavy ions which can destroy the target nucleus in a collision experiment ? To give an answer on which all the physicists interested in the field would agree is not easy. There is no doubt that new beams have been used by laboratories because it was an opportunity to do new experiments not feasible by other competing laboratories. This has given rise to a kind of race. Also, various reasons have been invoked to justify the funding of a new machine. However, I think that, presently, the main motivation to do heavy ion experiments, or at least the one which serves as a driving force for the development of the field is the study of the equation of state (EOS) of nuclear matter : what are the possible phases of this matter ? What are the properties of this matter, when density and temperature are varied ?

It might be surprising that nuclear physicists are so eager to know the EOS of a matter which appears in so small samples as the atomic nuclei. First of all, it is not true that there exist only small nuclear samples. As indicated in fig. 1, the nuclear matter appears in nature in large entities, the core of neutron stars, which can be considered as gigantic nuclei. Therefore the knowledge of the EOS of nuclear matter can help us to understand the structure and the formation of neutron stars. More importantly perhaps, the EOS of nuclear matter is the simplest information which embodies the properties of the strong or hadronic interactions, of which the nuclear force is the simplest exam-

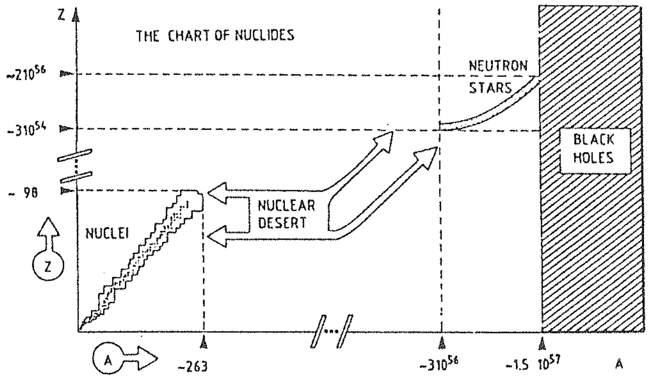

Fig. 1. Chart of nuclides. A is the number of nucleons, Z the number of protons. Adapted from de Rujula, CERN preprint 1985.

ple. We have now several pictures of nuclei, at various degrees of sophistication, depending of our view of the strong interactions. Just to quote a few, the nucleus can be regarded as a collection of point-like nucleons interacting through potential forces, or as a collection of point-like nucleons exchanging virtual mesons, or a collection of quarks interacting through the exchange of gluons (see section 5). The knowledge of the EOS can help us to discriminate between these pictures.

Before going further, let us mention that heavy ion beams are useful to other branches of physics (studies of nucleosynthesis, radiation damage, sputtering, track registration), to medicine (radiography and radiotherapy) and also to technology (ion implantation, fusion). This kind of activity is steadily increasing.

2. The accelerators and the energy domain

For many years, several accelerators have delivered beams of various heavy ions to up to an energy of 10 MeV per nucleon (this is the conventional way to give the energy of the beam). All these accelerators are coming close to the end of their period of activity. This region is usually called the low energy domain. Since 1975, the domain between 250 MeV per nucleon and 2 GeV per nucleon has been intensively studied, mainly at the Bevalac in Berkeley but also recently at Dubna and at Saclay. This domain is referred as the relativistic heavy ion domain, because the initial velocity of the ions is a substantial fraction of the velocity of light. Surprisingly, the intermediate region, named in fig. 2 the transitional region, has been opened only recently with the MSU500 (Michigan) and the GANIL (Caen) facilities. This field is the place for a technological breakthrough with the use of superconducting magnets (MSU500 and future machines at Gröningen and Uppsala). Finally, the ultra relativistic domain (> 2 GeV per nucleon) will be opened next year with the implementation of ion sources on existing high energy machines at Brookhaven and at CERN, but dedicated machines are expected to be built in the nineties.

3. The basic physics at low energy

There are at least three remarkable parameters on the energy scale shown on fig. 2. These are B/A, the average binding energy per nucleon of nuclei (≈ 8 MeV), E_F, the Fermi energy, i.e. the maximum kinetic energy of a nucleon inside an ordinary nucleus and E_{12}, which roughly is the energy above which an incident nucleon (in the projectile) can "resolve" the individual nucleons inside the target because its de Broglie wavelength becomes short enough.

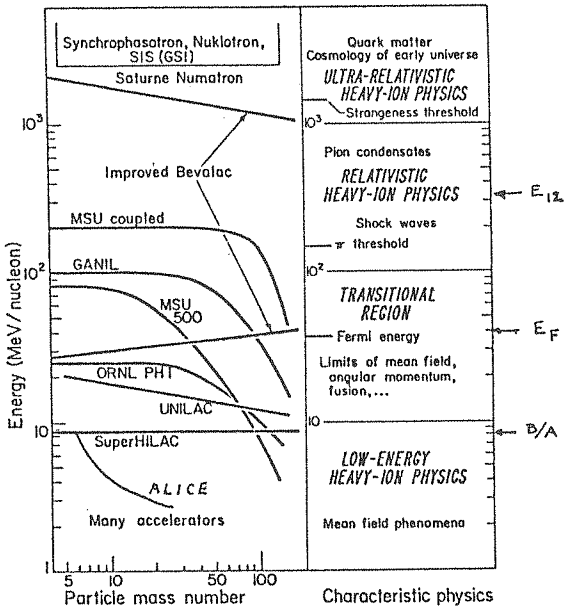

Fig. 2. Schematic presentation of the main accelerators. The curves indicate the typical energy reached by the accelerators as a function of the mass of the ions. The usual division of the energy domain is shown on the right.

The physics is expectedly different when one of these characteristic parameters is crossed over. Furthermore, the phenomena also change with the impact parameter b. This, of course, complicates the analysis, since there is no a priori control of this quantity. It can, however, be assigned qualitatively by looking at the gross properties of the events (an event is a single reaction).

At low energy, there is a huge variety of phenomena, depending upon the impact parameter. Grossly speaking, for very large parameters, the nuclei are passing close by each other and are weakly disturbed. For central collisions (small b), the two partners stick together and finally form a single nucleus, realising a fusion reaction. In the intermediate impact parameters, the nuclei come into close contact, exchange energy, mass and charge, but eventually separate in two entities. Those kind of events are named deep inelastic collisions. Although there are a lot of many interesting and curious features in these phenomena (like quantum diffraction, quantum rotations,...), these collisions can be understood as due to the same basic features responsible for the low energy excitations of a single nuclei : the underlying picture is an independent motion of nucleons inside a potential well or mean field, which can vibrate and deform owing to the action of the nucleons on its surface. From the theoretical point of view, there is however not yet a unified approach to the two kinds of processes. Also, the understanding of the coexistence of both single-particle and collective features from the basic nuclear forces is not complete yet.

4. The relativistic domain

The relativistic domain is lying almost entirely above the characteristic parameter E_{12} . Here, the collisions are usually violent, leading to a substantial compression and heating of the matter participating to the collisions. The basic mechanism of interaction is a succession of nucleon-nucleon collisions proceeding (almost) as in free space. Because of the available energy, pions and other particles can be created. Fig. 3 shows a simulation of a collision (seen in the c.m. frame) between two Au nuclei at an intermediate impact parameter. As time proceeds (note the very short time scale, 1 fm/c = 0.3×10^{-23} sec!), the matter is highly compressed near the centre of the system. The maximum density is around three times normal density. The associated temperature is around 70 MeV/k (about 10^{11} K!). A strong pressure is built inside the system, which gives rise to a rapid expansion. The two "horns" in the latest stage distribution is due to a few nucleons which initially are contained in the part of the projectile (target) which does not intercept the target (projectile) and which have made no collision : the so-called spectators. The very presence of the latter as well as the short time scale of the process indicate that the matter is the seat of off-equilibrium processes. Therefore it is understandable that the extraction of equilibrium properties, like the EOS is not straightforward. The best that has been done up to now is to compare the observables with the prediction of a theory which does not include compression energy, but which on the other hand is the most appropriate to handle off-equilibrium effects. This model is the intranuclear cascade model, which is equivalent to a numerical solution of a generalized Boltzmann equation. A typical result is shown in fig. 4, which gives the compression energy of the (cold, T = 0) nuclear matter as a function of its density. This corresponds to a stiff EOS. Its consequences are important, but will not be discussed here. The observable considered in this case is the number of produced pions, a quantity which can be shown to be intimately related to the thermal energy of the system, i.e. the available energy minus the compression energy. No doubt that the next future will bring us other similar information concerning the EOS.

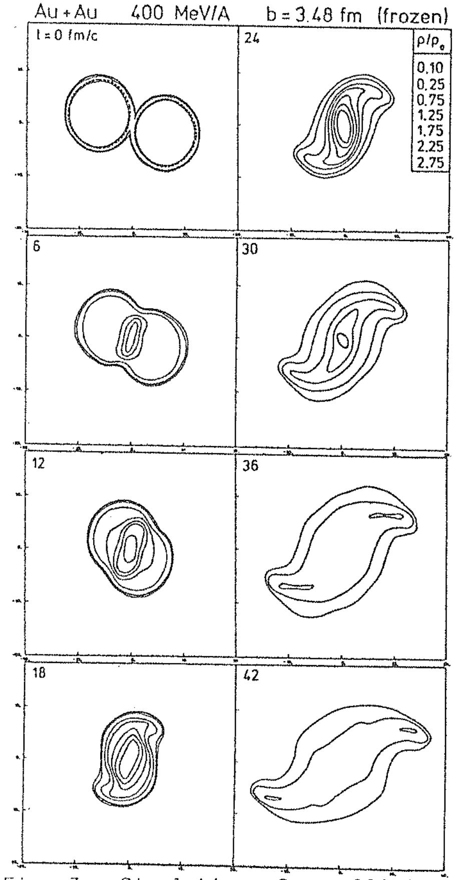

Fig. 3. Simulation of a collision between two Au nuclei. The lines are isodensity curves for successive times. The density, in terms of usual nuclear matter density, can be read from the numbers in the insert, the most external line corresponding to the smallest number. The calculation has been performed by D. L'Hôte from Saclay and the author.

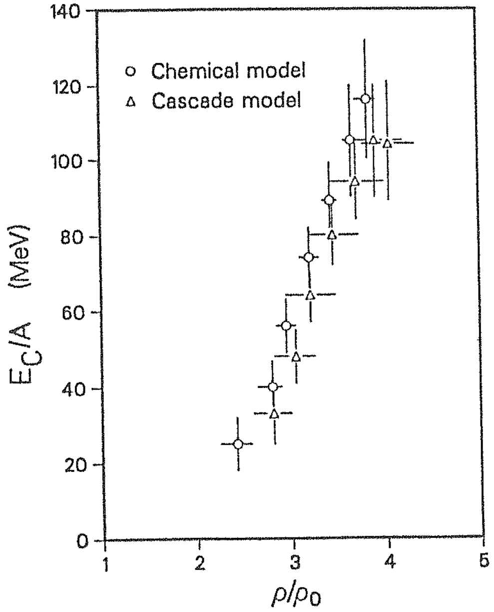

Fig. 4. Compression energy per nucleon of nuclear matter versus density ρ , as extracted from relativistic heavy ion collisions (see text). ρ_0 is the ordinary nuclear matter density. From R. Stock et al., Phys.Lett. 153 B(1985)377.

5. The phases of nuclear matter

In recent years, there has been a large amount of theoretical work gradually leading to the idea that nuclear matter can exist in many different phases (see fig. 5), and not only as a (Fermi) liquid as in ordinary nuclei. The latter are characterized by the heavy dot in fig. 5. It is not yet clear whether this liquid is superfluid or not. The possible existence of the phase named "quark-gluon plasma" at the upper right corner of the figure results from the most fundamental theory of strong interactions, called Quantum Chromodynamics (QCD). In this theory, the quarks (fermions) interact with gluon (boson) gauge fields, in very much the same way as electrons interact with photon gauge fields in Quantum

Electrodynamics (QED). Like the photons, the free gluons are massless. The electrons posess an electric charge, source of the electromagnetic field. Likewise, the quarks posess a "colour" charge, source of the "colour" field, whence the name QCD. However, there are three kinds of colours and this new aspect brings considerable complications and new features, which have no counterpart in QED. For instance, the gluons carry a (colour) charge. More importantly, the potential force acting between two quarks, to use a familiar picture, behaves like $1/r$ at small relative distances r, but increases very fast, when $r \to \infty$. Consequently two quarks cannot be separated. When more and more energy is brought inside a hypothetical two quark system, it eventually breaks into two or more $q\bar{q}$ (quark-antiquark) systems. These properties are responsible for the following organisation of the ordinary hadronic matter. Quarks are confined in small entities, the nucleons (the bags, in the usual terminology), which contain three of them, having mutually cancellating colors. The gluon fields generated by the quarks are also entirely contained within the nucleon. A quark and its antiquark can also be confined in a small volume to form a (colourless) meson.

When nuclear matter is squeezed to high densities, the bags start to overlap and continuous contact between quarks in different bags is established. They start to be deconfined. This deconfinement process is very similar to the transformation of ordinary matter composed of neutral atoms to an ordinary plasma. Extensive statistical mechanics calculations of a quark-gluon system (using a lattice approximation of space-time)indicate that there should exist a phase transition leading to a (colour) plasma of quarks and gluons. At low densities, the phase transition is expected around ten times ordinary density. Those conditions are not realized in present experiments, but will be hopefully met in experiments to be performed next year at the SPS at CERN at the AGS at Brookhaven. Oxygen and Sulfur beams will be accelerated at 200 GeV per nucleon and 15 GeV per nucleon, respectively. However, the way the plasma desintegrates and the way it can be identified is not clear yet. Several possible signatures will be investigated.

Fig. 5 indicates that nuclear matter can exist as a gas-liquid mixture, i.e. as an inhomogeneous system with parts at large density (the liquid) and with parts at low density (the gas). According to many authors, the isotherms of nuclear matter show loops typical of a van der Waals fluid. This is not really surprising, since nuclear force is repulsive at short distances and attractive at intermediate distances, a property that it shares with intermolecular forces. The critical temperature of nuclear matter is around 18 MeV k^{-1} and the critical density is about half of the ordinary density. This range of parameters corresponds to heavy ion collisions in the transitional region of fig. 2. As a matter of fact, many experiments have already been performed both at GANIL and at MSU to study this phenomenon. The basic idea is that the way an excited system in this temperature-density domain breaks into pieces should be influenced by the parameters of the expected gas-liquid transition. However, many complications blurred the analysis. The two most important ones are the following. First, the Coulomb repulsive energy (not negligeable as at higher energy) introduces another instability of the mixture. Second, the phase transition presumably occurs with spontaneous appearance and subsequent development of bubbles inside the nucleus. In the nuclear case, the size of the bubbles is of the same order as the size of the system, in contrast with ordinary liquids, where the bubbles are always very small. Intensive experimental as well as theoretical work is currently done. Alternative pictures of the fragmentation of the system are also investigated. Important progress is expected in the next few years.

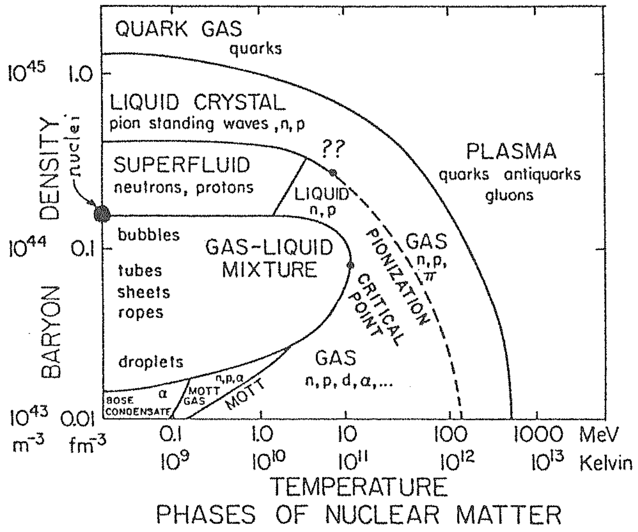

Fig. 5. Theoretical view of the possible phases of nuclear matter. Adapted from P.J. Siemens, Nucl.Phys. A428(1984)189c.

6. Conclusion

The development of heavy ion physics has required an extraordinary effort of the nuclear physics community in the world. This has been paid off already by the impressive collection of new results which have not been very much discussed here. Because of the short space available, I have concentrated on what seems to me the central question for the following years, namely the EOS of nuclear matter, or more generally, the thermodynamics of hadronic matter. This aspect is linked with our views of the intimate structure of matter. Heavy ion physics has brought new ideas and new insights in nuclear physics and has had implications on many aspects of research of our societies, ranging from astrophysics and cosmology to technology.

I wish to thank my friends, Drs. J. Vandermeulen, M. Bawin and A. Lejeune, for their advices and their criticisms.

For who wants to know more ...

Presently, there is no review embracing the whole filed of heavy ion physics. Here is a list of review papers generally devoted to one of the four domains only.

Low energy :

M. Lefort : "Main Trends in Heavy Ion Reaction Mechanisms on Energy Increases", preprint Orsay IPNO.DRE.85.15.
J.R. Birkelund and J.R. Huizenga, Ann. Rev. Nucl. and Part. Sciences 33 (1983) 26
M. Lefort : "Nuclear Structure and Heavy Ion Dynamics", Course LXXXVII, ed. by L. Moretto and R. Ricci (North-Holland Publ. C°, 1984) 208.

Intermediate energy :

C. Grégoire : "Non Equilibrium Processes in Heavy-Ion Collisions : From Fast Particles Emission to Hot and Fast Fission", preprint GANIL (Caen) P.85.03.
J. Hüfner : "Heavy Fragments Produced in Proton-Nucleus and Nucleus-Nucleus Collisions", preprint MPI H-84-V34 (to appear in Phys. Reports).

Relativistic energy :

S. Nagamiya et al., Ann. Rev. of Nucl. and Part. Sciences 34 (1984) 155.
S. Nagamiya et M. Gyulassy, Adv. in Nucl. Phys. 13 (1984) (Plenum Press, N.Y. 1984) 201.
R. Stock, preprint GSI-85-17, to be publisehd in Phys. Reports.

Ultrarelativistic energy :

"Quark Matter Formation and Heavy Ion Collisions", ed. by. M. Jacob and H. Satz (Word Scientific Pub. C°, Singapore, 1982).
"Quark Matter '84", ed. by K. Kajantie, Proceedings of the Helsinki Conferenc Lecture Notes in Physics vol. 221 (Springer-Verlag, 1985)
H. Satz : "The Transition from Hadron Matter to Quark-Gluon Plasma", preprint BI-TP- 85/01 (to be publisehd in Ann. Rev. of Nucl. and Particle Science, vol. 35 (1985)).