Nuclear opacity from low to relativistic energies

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Abstract

Hydrodynamic-like behaviour is one of the main global features of nucleus-nucleus collisions. It causes strong absorption and a sharp cut-off picture at low and presumed full nuclear stopping at high energies. There are, however, exceptions to complete nuclear opacity and several such examples from low to high energies are discussed here.

1 Introduction

The range of nuclear interaction is of the same value as the spatial extent of a nucleon, i.e. $\sim$1 fm. Therefore, nuclear interaction saturates and nuclei display behaviour typical of liquids which are macroscopically characterized as fluids resistive to compression and microscopically by vanishing mean-free-path. Owing to their hydrodynamic-like properties the global feature of low-energy nuclear dynamics is strong absorption and a sharp cut-off picture. Complete nuclear opacity is also expected at high energies. Nevertheless, there are examples of incomplete nuclear opacity which may manifest as surface transparency (incomplete absorption) or as incomplete stopping, i.e. a certain degree of nuclear pseudotransparency or non-equilibration.

2 Low energies

At low energies, when colliding nuclei overcome the Coulomb barrier and come into contact, the entrance channel longitudinal motion is entirely dissipated mainly due to one-body viscosity (rearrangement of the nuclear mean field from a two-centre to a single potential well). The colliding system is stopped and equilibrated. A single cold residue is formed at the end of the reaction – a fusion nucleus, whose mass corresponds to the full system mass. The two initial Fermi spheres completely overlap and nucleon-nucleon (NN) elementary collisions are frozen owing to the Pauli exclusion principle. Binary processes are restricted to elastic and inelastic collisions and transfer reactions around the Coulomb barrier and to quasi-elastic and deep-inelastic collisions (DIC) above several times the Coulomb barrier up to below the Fermi energy.

Already around the Coulomb barrier, however, a number of light up to medium heavy projectile-target combinations exhibit a phenomenon of orbiting, i.e. they create the so-called *nuclear molecules*. Qualitatively, a colliding system is made of a touching configuration of target and projectile nuclei which orbit around the common centre of mass and form a quantum-mechanical rotator displaying a characteristic rotational band of states (resonances) of intermediate width [1]. To observe molecular resonances, colliding nuclei should neither reseparate nor fuse into a compound nucleus before exhibiting an appreciable portion of rotation. This picture implies an unusually weak absorption of the grazing partial waves, which ensures the ("covalent") surface binding of the system and prevents its collapsing into a compound nucleus. One speaks of *nuclear-surface transparency*.

At energies of about 10 MeV/nucleon, scattering of a few light nuclei with the closed shells or subshells exhibits a phenomenon of *nuclear rainbow*: Several peripheral partial waves are refracted to the same scattering angle at which the differential elastic cross section is strongly enhanced [2]. Refractive phenomena imply that these (semi)closed shell nuclei exhibit an exceptional *transparency of nuclear periphery*.

Interestingly enough, the same nuclear systems display refractive (rainbow, $E \geq 10$ MeV/nucleon) and enhanced orbiting (nuclear molecules, $E \leq 5$ MeV/nucleon) behaviour. Therefore, it has been speculated that they may display, in the intermediate energy range (5 to 10 MeV/nucleon), Airy oscillations, a refractive phenomenon of higher order [2]. Recently, an analysis of carefully measured elastic scattering of carbon and oxygen nuclei in the full angular range has shown the existence of Airy structures [3, 4]. As an example, Fig. 1 shows the $^{16}\text{O} + {}^{12}\text{C}$ elastic scattering angular distribution measured at 115.9 MeV (circles) together with an optical model fit (dotted curve) and the "nuclear" component (full curve) of the nearside-farside decomposition of the fit function [4]. The sharp minima in the farside "nuclear" component are due to the interference of a bunch of peripheral waves (rainbow refraction) with a low-l deeply penetrating partial wave and are attributed to the Airy minima of different orders [4]. The regularity of the angle of appearance of a given minimum with energy (see Fig. 2 [5]) endorses our conclusion. In the elastic scattering of these (semi)closed shell

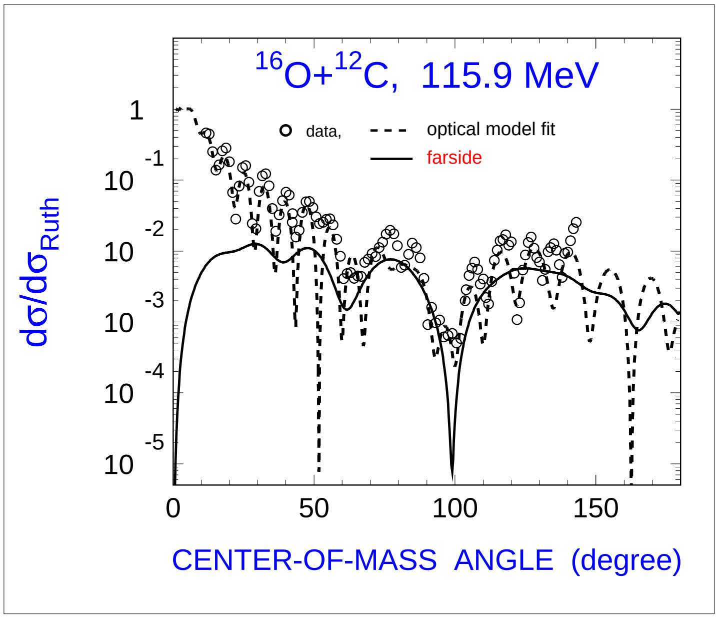

Figure 1: The $^{16}O+^{12}C$ elastic scattering angular distribution measured at 115.9 MeV. The dotted curve is due to the optical model best fit of the data (circles) and the full curve represents the farside ("nuclear") component resulting from the nearside-farside decomposition of the fit function [4].

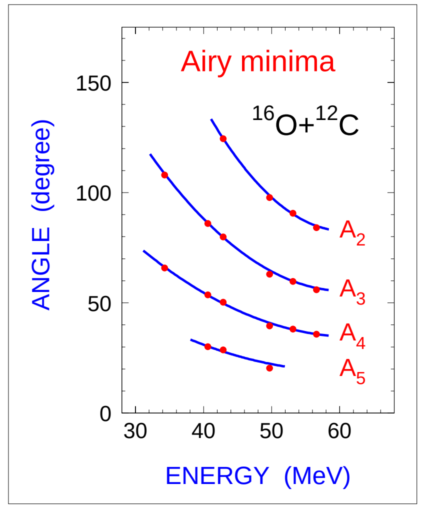

Figure 2: Plot of incident energy against angle-of-appearance of the attributed Airy minima of different orders for the $^{16}O+^{12}C$ elastic scattering [5].

nuclei one is facing the phenomenon of *nuclear interior transparency*, a pure quantum-mechanical feature incompatible with a classical liquid.

3 Relativistic energies

At the other end of in-the-laboratory-available energies are ultrarelativistic collisions. At these energies one also expects full nuclear opacity in the zone of the geometrical overlap of colliding nuclei (the participant–spectator picture and a fireball formation) owing to the two-body dissipation of the entrance channel longitudinal motion via elementary NN collisions. A transiently stopped nucleons are assumed to deconfine and create plasma with the equilibrated quark-gluon degrees of freedom.

In contrast to these extreme energies, a dedicated experiment aiming at evidencing the degree of nuclear equilibration and stopping, has recently been performed with the FOPI detector at energies of about 1 GeV/nucleon [6]. At these energies some effects of the nuclear mean field on the dynamics of the nucleus–nucleus interaction may still be present. The isospin tracing technique was used in mass symmetric reactions with four possible projectile-target combinations of the ${}^{96}_{40}$Zr ($N/Z = 1.40$) and ${}^{96}_{44}$Ru ($N/Z = 1.18$) nuclei [7]. The N/Z ratio in a given cell of phase space is used to attribute the measured nucleons (on average) either to the target or to the projectile nucleons. In this way, one can, on a model-independent basis, extract rapidity distributions separately for projectile and target nucleons. The isospin symmetric reactions Zr + Zr and Ru + Ru serve as a reference, while the isospin asymmetric reactions Zr + Ru and Ru + Zr directly infer on the degree of isospin mixing between projectile and target nucleons. Thus, a direct information on the chemical (and indirectly global) equilibration of the system as a function of reaction centrality can be drawn. As an example, Fig. 3 displays the Ru + Ru proton rapidity distribution measured at 400 MeV/nucleon (open circles) for the subset of the most central collisions. Although the distribution is peaked at mid-rapidity, which is a necessary condition for stopping, application of the isospin tracing procedure discussed above disentangles target (filled triangles) from projectile (filled squares) contributions which appear as mutually separated making evident a relative collective motion of projectile and target nucleons [7]. Obviously, the global isospin equilibration is not reached even in the most central collisions. The fact that the mean of the projectile component (filled squares) is at positive values of relative rapidity implies a certain degree of nuclear transparency. We call it *pseudotransparency* to mark a substantially different nature of these collisions relative to the low-energy elastic scattering. As a qualitative measure of the nuclear stopping power, i.e. of the pseudotransparency, taken is a relative number of forward ($N_{\rm forw}$) to backward ($N_{\rm back}$) moving nucleons of the projectile in the most central collisions:

$$M_{\rm proj} = \frac{N_{\rm forw} - N_{\rm back}}{N_{\rm forw} + N_{\rm back}}.$$

At 400 MeV/nucleon, $M_{\rm proj} = 0.17$ [7], while a similar preliminary analysis of the data taken at 1.5 GeV/nucleon gives about twice greater pseudotransparency ($M_{\rm proj} \approx 0.4$) [8].

4 The Fermi energies

The MSU–Texas A&M University investigation of the isotopic ratios of emitted fragments from a couple of carefully chosen isospin asymmetric systems has demonstrated that the reaction passes from chemically equilibrated to non-equilibrated behaviour as the incident energy increases from below to

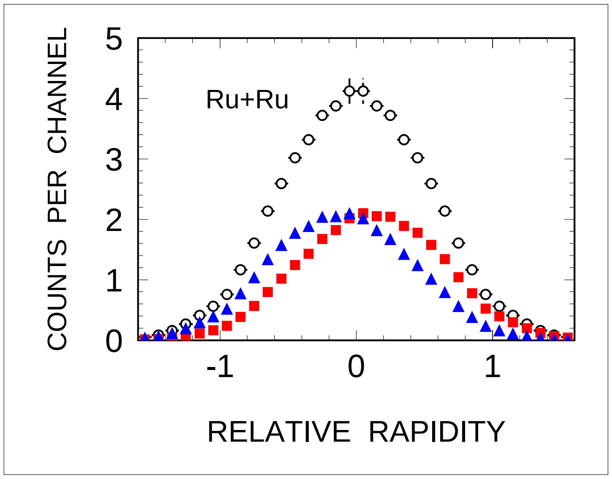

Figure 3: Proton rapidity distribution of the Ru+Ru central reaction ($b < 2$ fm) measured at 400 MeV/nucleon. Filled squares display the contribution of the projectile and filled triangles of the target nucleons in the measured distribution (open circles) [7].

above the Fermi energy [9]. The change of the global reaction feature around the Fermi energy is not theoretically unexpected. The Fermi energy region is a genuine transition region in which the nuclear mean field starts to weaken, while the available phase space for NN collisions quickly opens as the energy increases making the Pauli principle less and less efficient in blocking the elementary NN collisions [10]. Let us show that there are other examples corroborating the transition character of this energy range.

Since the entering of a new generation of 4π multidetectors into exploitation (90-ies of the last century), a large amount of experimental evidence has been accumulated showing that the reaction dynamics around the Fermi energy is strongly dominated by binary processes of highly dissipative character, the so-called *binary dissipative collisions* (BDC) (see, e.g. [11] and references therein): Two massive, more or less excited fragments, quasi-projectile (QP) and quasi-target (QT), are present in the reaction exit channel irrespectively of the collision centrality. It is a fundamental question whether the reaction mechanism of BDC is an extension of DIC to central collisions or whether it represents advanced signs of high-energy processes. The validity of the former hypothesis would lead one to postulate the existence of extremely hot nuclei offering the opportunity of thermodynamic-type studies and, in particular, of the characterization of the nuclear matter equation of state. Contrarily, if the latter hypothesis is true, a large amount of available energy would be promptly evacuated from the interaction zone formed by the two overlapping collision partners. This would lead to a substantial reduction of the excitation energy of the primary QP and QT.

The answer to the above crucial question could be given only via a detailed theoretical analysis using the dynamical model of high performance allowing the close follow-up of the realistic simulation of the collision evolution. We have performed theoretical studies of heavy-ion collisions around the Fermi energy in the framework of the microscopic Landau-Vlasov [12] model in which the quantum extended Boltzmann equation is solved for a non-local effective force (Gogny D1-G1, the incompressibility modulus K_{∞}=228 MeV and the effective mass m^{*}/m=0.67). In a fully microscopic approach, the kinetic equations of the LV model account for all sources of dissipation, i.e. the mean field and NN collisions. According to our studies, an appreciable amount (up to 50 %, depending on reaction centrality, incident energy and system) of the system mass and available energy is *promptly dynamically* dissipated during the early compact phase of the collision [11, 13]. This finding has recently been confirmed experimentally [14]. The prompt emission component is mainly sitting at mid-rapidity and the amount of this dynamically emitted matter is proportional to the geometrical overlap of colliding nuclei [11, 13]. Consequently, primary QP is neither very massive nor very hot [10, 15].

Detailed theoretical studies reveal that even in head-on collisions about 2/3 of the primary QP (QT) mass is from the projectile (target) [10, 11]. The QP and QT pass through a transient extremely elongated dinuclear type of deformation and separate with a small relative velocity keeping the entrance channel direction of motion [10, 16]. Collision displays a strong memory of the entrance channel motion (no full stopping) and an incompleteness of chemical equilibration (no full mixing of projectile and target matter). One faces a phenomenon of *nuclear matter pseudotransparency*. In addition, it stems out that the reaction dynamics precludes the formation of a fusion nucleus. *Binary processes amply open in central collisions around the Fermi energy since the mean field becomes too weak for full stopping of the colliding nuclei, while NN collisions do not set in in their full strength yet owing to the still important Pauli blocking.* However, NN collisions govern the interaction zone, so that these binary dissipative collisions are closely related to the participant-spectator scenario rather than to the low-energy deep-inelastic phenomena.

The phenomena discussed above (ample opening of the binary channel, incomplete stopping, incomplete matter mixing or incomplete chemical equilibrium, memory of the entrance channel motion, strong matter and energy dissipation prior to scission, primary QP and QT separation with small relative velocity) are closely related and can be understood as an underlying consequence of unbalanced one- and two-body effects around the Fermi energy. They may have tremendous consequences on the properties of hot nuclei formed in heavy-ion collisions at these energies. A model-independent experimental proof of nuclear *(pseudo)transparency* as a cause of the dominant binary nature of heavy-ion collisions around the Fermi energy is urgently needed. In this direction, an experiment at the Catania cyclotron is proposed making use of the isospin observable with the intention of proving lack of complete chemical equilibration in very central collisions [17].

In the proposed experiment the N/Z ratio of reaction products will be deduced by direct detection of mass and charge in a collision between nuclei of a different initial relative abundance of protons to neutrons [17]. As discussed at high energies [7], the isospin degree of freedom allows to follow more directly how matter is transported between collision partners, i.e. how protons and neutrons (nucleons) mix and propagate in the medium. We have demonstrated via LV model simulation [17] that, to completely determine the collision process of our interest, it is, in principle, sufficient to detect velocity/energy, mass and charge of the forward emitted QP. In the choice of the reaction system one has to compromise between not too small nuclei which risk to vaporize in central collisions and not too large nuclei which may lead to the usual fusion-fission process. Symmetric systems are more favorable since they have a smaller chance for the fusion-fission process. The most decisive is, nevertheless, that the projectile and the target differ in the N/Z ratio as much as possible since the strength of the signal will depend substantially on the initial isospin asymmetry. In the whole chart of nuclides we find that the best choice is $^{48}_{20}\mathrm{Ca}_{28}$ for the projectile $[(N/Z)_{proj} = 1.4]$ and $^{40}_{20}\mathrm{Ca}_{20}$ for the target $[(N/Z)_{targ} = 1.0]$. The energy must be sufficiently high to ensure an ample binary contribution even in the most central collisions. We propose to set the energy at 40 MeV/nucleon.

The double-hatched zone in Fig. 4 delimits the values which the observable of our interest here, the QP N/Z ratio, takes as a function of b. The dashed horizontal line at $N/Z = 1.4$ corresponds to $(N/Z)_{\mathrm{proj}}$ and that at $N/Z = 1.2$ corresponds to the value which the N/Z ratio would take for a chemically equilibrated system. The hatched area delimits a zone with $b < 2.2$ fm (i.e. $b/b_{\mathrm{max}} < 0.25$) and within it the N/Z ratio takes values $N/Z = 1.29 \pm 0.02$. On the other hand, for full stopping of the entrance channel motion and for establishing of chemical equilibrium one would have $N/Z = 1.20 \pm 0.02$. We hope that sufficient experimental

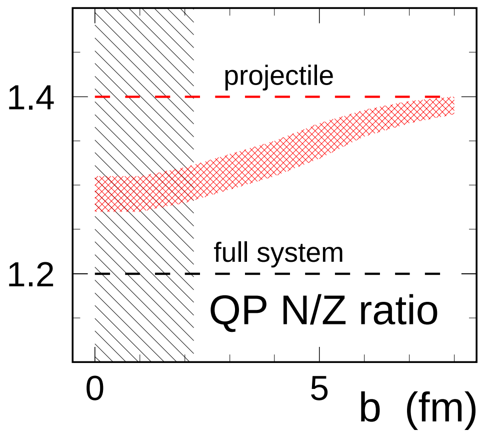

Figure 4: LV model simulation of the $^{48}Ca + ^{40}Ca$ collisions at 40 MeV/nucleon. Shown is the quasi-projectile N/Z ratio as a function of b.

precision can be reached allowing to unambiguously confirm or deny our theoretical predictions.

5 Conclusions

In this contribution, nuclear opacity and examples of its violation have been discussed. Incomplete nuclear opacity manifests as surface transparency (incomplete absorption) at low energies or as incomplete stopping, i.e. a certain degree of nuclear pseudotransparency or non-equilibration at intermediate and high energies. A theoretical indication that nuclear pseudotransparency is the underlying physical cause of binary dissipative collisions which amply open around the Fermi energy has been discussed at length. An experimental confirmation of this theoretical prediction would have a great influence on thermodynamic studies at energies below 100 MeV/nucleon and an experiment in this direction has already been proposed.

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