FROM WOUNDED NUCLEONS TO NUCLEAR STRUCTURE

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The wounded nucleon model was invented to account for the multiplicity of particles produced in nucleus–nucleus collisions. As such, it emphasizes the features of particle production along the collision axis. It contains, however, another important aspect, which is the main focus of this note, that the early stages of high-energy nuclear collisions are determined by the locations of the wounded nucleons in the transverse plane. Thanks to the high-precision data of the LHC, this may, in return, be used to infer fine nuclear structure aspects of the colliding nuclei.

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1. Wounded nucleons

The wounded nucleon model [1] was introduced to provide a simple phenomenological understanding of the multiplicity of particles produced in nucleus–nucleus collisions. To set the stage, consider a proton–nucleus collision. Assuming that the proton collides independently with each of the nucleons that it encounters in its trajectory through the nucleus (see Fig. 1), and that each collision produces the same multiplicity as in a nucleon–nucleon collision, one would expect the multiplicity to grow proportionally to the number of collisions. In fact, one could even expect an exponential growth of produced particles if one takes into account that each secondary particle has the possibility to interact within the nucleus, producing in turn additional multiplicity, the so-called intra-nuclear cascade. This is not observed.

Instead, the first collisions at RHIC indicated that the multiplicity n_{pA} in high-energy proton–nucleus collisions was accurately given by the simple formula [2]

$$n_{pA} = \frac{1}{2}(\nu_A + 1) n_{pp} \,, \tag{1}$$

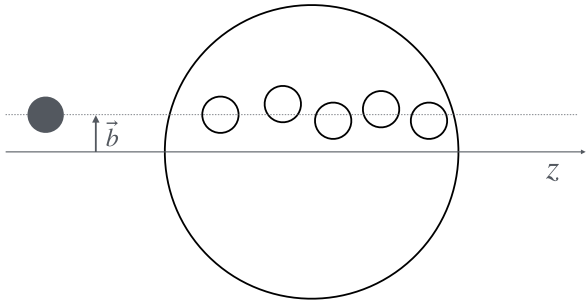

Fig. 1. The wounded nucleons in a pA collision. The proton (black disk) and all the nucleons of the nucleus (open circles) which sit on its trajectory (with which it suffers inelastic collisions) are "wounded".

where ν_A denotes the average number of nucleon–nucleon inelastic collisions and n_{pp} is the multiplicity in a nucleon–nucleon collision. One would have expected rather a formula like $n_{pA} = \nu_A n_{pp}$. The concept of wounded nucleon provides a nice interpretation of the formula[1]. A wounded nucleon is a nucleon that undergoes at least one inelastic collision in the process considered. For instance in the pA collisions that we are discussing, the proton and all the nucleons of the nucleus with which it interacts inelastically are wounded. The previous formula can then be rewritten as $n_{pA}/n_{pp} = \frac{1}{2}w$, where w is the number of wounded nucleons. This is interpreted by saying that each wounded nucleon contributes the same amount to the multiplicity, irrespective of how many collisions it suffers. The power of this concept becomes more manifest in the case of nucleus–nucleus collisions, where the authors of [1] proposed the following generalisation:

$$n_{AB} = \frac{1}{2} w_{AB} n_{pp} \,, \tag{2}$$

where now w_{AB} is the average number of wounded nucleons in the collisions of nucleus A on nucleus B. This number is clearly much smaller than the average number of independent nucleon–nucleon collisions involved in the collision of A on B.

Under the assumption that the nucleus–nucleus collision can be viewed as a superposition of independent (incoherent) nucleon–nucleon collisions, one can calculate the average number of wounded nucleons in terms of cross sections. For the pA collision, we have $\nu_A = A\sigma_{pp}/\sigma_{pA}$, where σ_{pA} and σ_{pp} are, respectively, the inelastic cross sections in pA and pp collisions. For the

[1] For a personal account on the genesis of the idea, and the origin of the terminology, see [3].

AB collisions, we get $w_{AB} = w_A + w_B$, with

$$w_A = \frac{A\sigma_B}{\sigma_{AB}}\,, \qquad w_B = \frac{B\sigma_A}{\sigma_{AB}}\,, \tag{3}$$

where σ_{AB}, σ_A, σ_B are, respectively, the inelastic cross sections for the collisions AB, pA, pB. The multiplicity given by Eq. (2) involves then only quantities that can be determined experimentally. It represents therefore an important test of the underlying assumption. The model has met great success in explaining multiplicity distribution in nucleus–nucleus collisions, and it is used routinely to analyse heavy-ion data, in particular to determine the centrality of the collisions from the multiplicity. The model has been refined to include nucleon constituents (quarks and diquarks) in order to get a better description of the multiplicity distributions [4].

The concept of wounded nucleon is a simple and fruitful idea, and as we just recalled, is phenomenologically successful. On a more theoretical side, we note that it emphasises the physics of particle production that proceed mostly along the longitudinal direction (collision axis). In particular, the absence of intra-nuclear cascade is well explained by the fact that particles are not produced instantaneously, nor locally along the collision axis. There is a "formation time", or equivalently a "formation zone" that can be much larger than the size of the system: thus, no secondary interaction within the nucleus, therefore, no intra-nuclear cascade. This suppression mechanism, as well as others mechanisms implied by a variety of models of particle production, is likely involved in the explanation for the scaling of the multiplicity with the number of wounded nucleons. However, my main subject here concerns what happens in the transverse plane where the initial density of wounded nucleons determines the collective evolution of the produced matter.

As a transition to what follows, I would like to quote the final remark of the paper just cited [4]: "...in all hadronic collisions, the early stage of the particle production process can be understood as a superposition of contributions from hadronic constituents. This does not preclude further collective evolution of the system which obviously must be more visible in the system produced in collision of two heavy nuclei than in a nucleon–nucleon collision. **The wounded constituent picture suggests, however, that most of the entropy is produced already at the very early stage of the process.**"

2. Glauber modelling of high-energy collisions

Glauber's theory of multiple scattering [5] underlies the picture of wounded nucleons. It does not clarify the mechanisms of particle production alluded to earlier, but it provides a consistent framework to handle many aspects of multiple scattering at high energy (such as, for instance, the determination of the distributions of wounded nucleons). With the help of phenomenologically motivated adjustments, it has become an invaluable tool to describe the main features of high-energy heavy-ion collisions. Its numerical implementation is commonly referred to as Glauber Monte Carlo model, its optical limit being often used in applications [6, 7].

Relying on the eikonal approximation, with particles moving on straight line trajectories, it provides an intuitive, geometrical picture of the collisions in which the density of the wounded nucleons in the transverse plane plays a major role. As stated above, the wounded nucleon model suggests that the entropy is produced locally in the transverse plane, precisely where nucleons are wounded along their straight line trajectories. This entropy density determines, in particular, the initial conditions for the subsequent evolution of the matter.

A typical picture of the distribution of wounded nucleons in the transverse plane is given in Fig. 2. This figure indicates that, irrespective of the fluctuations associated with the particle production mechanism, the local density of participants is not smooth, which reflects the fluctuations of the positions of the wounded nucleons. Indeed, while in a given collision, the transverse positions of the wounded nucleons can be considered as frozen, these positions change event by event. They may be regarded as random variables, the probability distribution of a given configuration of postions in one nucleus being given by the square of the many-body wave function, or more precisely its projection on the transverse plane, *i.e.*,

$$|\Psi_0(\boldsymbol{s}_1,\ldots,\boldsymbol{s}_A)|^2=\int \mathrm{d}z_1\ldots\mathrm{d}z_A\,|\Psi_0(\boldsymbol{r}_1,\ldots,\boldsymbol{r}_A)|^2\,, \tag{4}$$

where $\boldsymbol{r}=(\boldsymbol{s},z)$, with z being the projection of $\boldsymbol{r}$ along the collision axis. In principle, the average over events that needs to be done in order to calculate observables should involve this probability distribution $|\Psi_0(\boldsymbol{s}_1,\ldots,\boldsymbol{s}_A)|^2$. However, in many applications, a simple approximation is used, namely

$$|\Psi(\boldsymbol{r}_1,\ldots,\boldsymbol{r}_A)|^2\mapsto\rho^{(1)}(\boldsymbol{r}_1)\ldots\rho^{(1)}(\boldsymbol{r}_A)\,, \tag{5}$$

where $\rho^{(1)}(\boldsymbol{r})$ is the one-body density of the nucleus normalised to unity. This is usually taken to be a Woods–Saxon distribution $\rho^{(1)}(\boldsymbol{r})=\rho_0/(1+\mathrm{e}^{(r-R)/a})$. This is how Fig. 2 was obtained, by sampling the one-body density in a Monte Carlo Glauber calculation. This approximation ignores, of course, all the correlations contained in the many-body wave function. We shall return to this issue shortly.

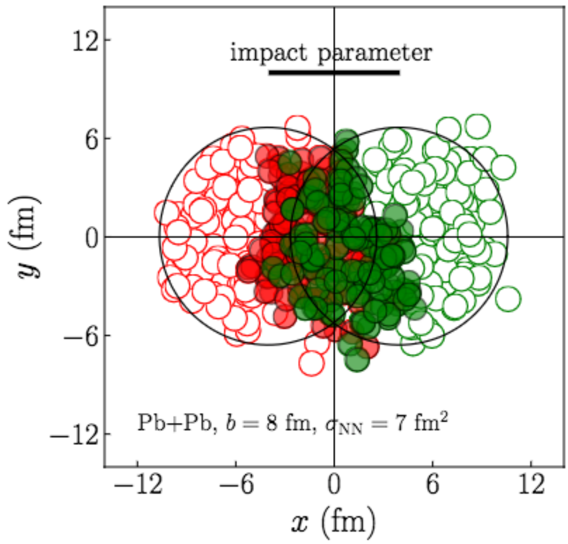

Fig. 2. Typical distribution of "participants" in a Glauber Monte Carlo calculation at some finite impact parameter. Figure taken from [8].

At this point, we note that the dynamics in the longitudinal direction is not resolved, it is integrated out in the probability distribution of the transverse positions. One of the important uses of the Glauber Monte Carlo calculation is to determine the pattern of entropy deposition in the transverse plane. This is important, in particular, to pin down the initial conditions for the hydrodynamic evolution of the quark–gluon plasma. The entropy density can be considered as a random field in the transverse plane [9], and its statistics comprise short-range and long-range fluctuations.

The short-range fluctuations depend in part on the details of the particle production mechanisms, which are poorly understood. One then resorts to phenomenology to determine the produced entropy. One may assume that the entropy density is deposited proportionally to the local density of participants, which leads to the so-called "participant scaling" (see *e.g.* [2], and reference therein)[2]. Some studies use a mixture of participants and number of binary collisions, or take into account subnucleonic degrees of freedom, quarks [10] or diquarks [11]. A more sophisticated prescription is the so-called T$_{\rm R}$ENTo model [12] that relates the entropy density to some functional of the thickness functions of the two colliding nuclei. In any case, this leads to uncertainties that affect mostly the local fluctuations, taking place in the transverse plane on length scales of order one fm or so.

[2] The term "participant" is synonymous with wounded nucleon provided one restricts that notion to those nucleons that suffer at least one inelastic collision, and exclude elastic scattering.

There is another aspect of short-range correlations which pertains to the correlation left out when using the factorized form of the probability distribution discussed above. This has been examined by various groups (see *e.g.* [13]). However, while these correlations may be important for the calculation of three-dimensional observables, their impact on the probability distribution (4) in the transverse plane is expected to be much attenuated. This is because two nucleons which appear to be close to each other in the transverse plane can be, in fact, far away in the longitudinal direction, hence blind to short-range correlations. The explicit calculation performed in [14] indicates that the reduction can be quite large.

Long-range correlations are of a different nature. Short-wavelength fluctuations average out in the calculation of long-wavelength observables. What remains after some evolution are the long-wavelength fluctuations (low multipoles, "collective variables") [15], in particular those that characterize the "shape" of the collision zone. These long-range fluctuations are those which determine the pattern of collective flows observed in heavy-ion collisions. Since these are determined at the initial stage of the collisions, they carry direct information about analogous fluctuations/correlation in the nuclei themselves. This is where the connection alluded to in the title comes in, as we discuss now.

3. Fluctuations and collective flows

Collective flows of the produced matter stand out among the most striking phenomena observed in ultra-relativistic heavy-ion collisions. Of particular interest in this discussion are those collective flows that are related to the anisotropy of the particle distributions. These turn out to be very sensitive to the shape of the distribution of the wounded nucleons in the transverse plane at the instant of the collision, while the subsequent hydrodynamic evolution keeps track of this initial shape till the end of the process. The mechanism giving rise to such collective flows is well understood in terms of pressure gradients which, in the case of the so-called elliptic flow, accelerate particles preferentially in the collision plane rather than in the orthogonal direction. More generally, the pattern of pressure gradients transfers the spatial anisotropy of the collision zone into an anisotropy of the measured momentum distributions. The Fourier analysis of the momentum anisotropy yields the flow coefficient v_n [16].

Monte Carlo Glauber calculations allow us to determine the initial shape of the collision zone from, in principle, the many-body wave functions of the colliding nuclei. These wave functions give the probability of a given configuration of positions in each event, leading to event-by-event fluctuations of these positions. To the extent that the dominant long-range fluctuations are determined by the many-body wave functions, their study can inform us in return about long-range correlations in nuclei, thereby providing a relation between nuclear structure aspects and measurements in heavy-ion collisions. This represents one of the exciting developments of these recent years [8].

While the idea is not new, as we shall recall shortly, what has changed in recent years is the high energy of the collisions at the LHC, which makes the nuclear dynamics completely frozen during the early stages of the collisions. In addition, the large multiplicities, and the high statistics, lead to precise data, and allow for detailed studies of ultra-central collisions, where the impact parameter essentially vanishes [17].

There is plenty of experimental evidence for the role of the fluctuations of nucleon positions in determining the collective flow. The first strong evidence came from the observation of significant elliptic and triangular flows in central Cu–Cu collisions [18]. This was, in fact, a breakthrough, since the common expectation before the results were reported was that central collisions of spherical nuclei could not generate a collective flow whose origin lies precisely in the anisotropy of the wounded nucleon distribution. However, zero point fluctuations can generate, event by event, shapes with some excentricity. This is the origin of the observed v_2 and v_3. Since then, there have been many confirmations of the phenomenon, among those, let me just mention the remarkable results from isobar collisions (see the collective review [19] which contains a large number of references on this very rapidly developing field). Worth mentioning is also the detailed analysis of collective flows in Pb–Pb collisions leading to a precise estimate of the neutron skin [20].

Note that all the examples just quoted involve essentially sampling the one-body density. Things are different when deformed nuclei are considered. The impact of nuclear deformation in heavy-ion collisions has been recognized long ago. For instance, one of the early ultra-relativistic heavy-ion collisions involved collisions of ^{32}S on ^{238}U and other nuclei. It was observed that the tail of the transverse energy ($E_{\rm T}$) distribution, corresponding to the most central collisions, extended to larger values of $E_{\rm T}$ for U than for other nuclei with similar masses but spherical. This was naturally interpreted as a consequence of the deformation of the uranium nucleus, the produced transverse energy being dependent on the orientation of the uranium at the moment of impact with the sulfur nucleus [21]. Other phenomena involving the shape of an underlying intrinsic state are those connected to clustering in nuclei, which has been considered in [22].

To take into account nuclear deformation in a Glauber calculation, one needs to improve on the sampling of the one-body density. One typically assumes a one-body density of the form (limiting the discussion to quadrupole deformation for simplicity)

$$\rho(\boldsymbol{r}) = \frac{\rho_0}{1+\mathrm{e}^{(r-R(\theta))/a}}\,, \qquad R(\theta) = R_0\left(1+\beta_2 Y_{20}(\theta)\right)\,. \tag{6}$$

This is taken to be the density of the intrinsic state which, with the given parametrization, possesses a quadrupole moment. One then defines a density $\rho_\Omega(\boldsymbol{r})$, corresponding to the intrinsic density rotated by some Euler angles denoted collectively by Ω. After the sampling of the one-body density, an angular average is performed so as to respect the rotational symmetry of a $J=0$ ground state. In the intrinsic state, the n-point functions are trivial (no correlation), so that for instance, the two-point function reads $\rho^{(2)}_\Omega(\boldsymbol{r}_1,\boldsymbol{r}_2) = \rho^{(1)}_\Omega(\boldsymbol{r}_1)\rho^{(1)}_\Omega(\boldsymbol{r}_2)$. However, after angular integration, we have

$$\rho^{(1)}(r) = \int\frac{\mathrm{d}\Omega}{4\pi}\rho_\Omega(\boldsymbol{r})\,, \qquad \rho^{(2)}(\boldsymbol{r}_1,\boldsymbol{r}_2) = \int\frac{\mathrm{d}\Omega}{4\pi}\rho^{(1)}_\Omega(\boldsymbol{r}_1)\rho^{(1)}_\Omega(\boldsymbol{r}_2)\,, \tag{7}$$

where $\rho^{(1)}(r)$ is spherically symmetric, and a non-trivial correlation emerges from the angular integration giving $\rho^{(2)}(\boldsymbol{r}_1,\boldsymbol{r}_2)$ [23]. Such a correlation is very similar to that used to determine the v_2. This procedure has met with considerable success, leading, in some cases, to predictions for deformation parameters which were poorly determined from low-energy experiments [24].

All these developments are accompanied by a series of interesting conceptual questions. For example, practitioners of so-called *ab-initio* calculations would argue that the concept of intrinsic state is really not needed and perhaps even misleading, that thinking of the uranium nucleus as having a definite orientation as it collides may be somewhat naive. Still, this semi-classical picture leads to a very successful phenomenology, and one may recall here that there is often a choice or representation in quantum mechanics, some representations making the underlying physics more manifest than others. One may also observe that nuclear deformation is accompanied by specific many-body angular correlations [23] that are of a classical nature (as discussed above) and these can be identified in the many-body wave functions without ever referring to an intrinsic state [25, 26]. This and other questions, such as, for instance, that of why the Glauber picture works so well, are among issues that clearly deserve further thinking.

4. Conclusions

It is remarkable that the locations of precisely where nucleons get "wounded" at the instant of the collisions is so well remembered by the final stages of heavy-ion collisions. Thanks to the high energy of the LHC collisions and the precision of the data, we are reaching the stage where nuclear structure issues can be addressed in the context of heavy-ion experiments. This is a remarkable and unanticipated exciting development in the field.

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