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ABSTRACT

Some selected aspects of nuclear reactions at beam energies below a couple of GeV/nuc are reviewed. The different dynamical regimes from the micro - to the macro dynamics and the late expansion stage are discussed and compared with respect to their implications on specific observables like inclusive data or global event observations.

1. Introduction

The purpose of my talk is to review some selected aspects of heavy-ion reactions at beam energies below a couple of GeV/nuc. The motivation being that in this range alongside with the rich experimental experience^{1,2)} many of the theoretical concepts could be explored, that now again are employed at the ultra relativistic regime, the topic of this work shop. Be it thermodynamics, hydrodynamics, cascade pictures, compression-, expansion- or energy deposition questions.

Let us therefore concentrate on the energy regime of a couple of 100 MeV/nuc c.m. energies. There, advantageously enough, we do believe to know the basic constituents and their mutual forces at least.

Quite a rich variety of models has been suggested and explored so far. They served a significant insight into the dynamical evolution of these reactions. Recall the role of geometry (Fig. 1), the notions

⁺invited talk at the workshop on Quark Matter Formation and Heavy Ion Collisions, Bielefeld, FRG, May 9-13, 1982; up-date of a similar lecture given at the 5th High Energy Heavy Ion Study, Berkeley, May 1981, LBL-12652.

of spectators and participants; with the two step fragmentation picture of abrasion and ablation at peripheral impact covering the low momentum parts relative to the projectile or target restframes, and with the violent or 'hot' participant component prevailing

Fig. 1. An illustration of the straight-line geometry in collisions between nuclei at high energy. An incoming projectile with momentum p_0 per nucleon plunges through the target. The nucleons from the overlap zone (shaded area) are called "participants". Only they collide and contribute to the one-nucleon inclusive cross section. The other nucleons (unshaded pieces) remain "spectators".

in central collisions. The latter component covers a relatively broad spectrum of final momenta centered between projectile and target rapidities with tails reaching the borders of phase-space at high momenta.

Rather than going into a detailed comparative discussion of the various approaches as already done by others on earlier occasions²⁾, rather than exposing the respective nice (or pretended) agreement with the data, I like to discuss some selected aspects. The guideline will be the course of the reaction in time from the early pre-equilibrium stage over the regime where macrodynamical effects may dominate towards the final expansion phase of the reaction.

11. The systematic of models

The most fundamental theoretical frame to begin with would be a relativistic quantum field theory of hadronic interactions. However, for the kinetic regime of reactions that we are interested in such an approach will not be practicable even in the far future. Thus we have to settle for less.

Ignoring particle production for a while, the quantum many-body density matrix in its time development is the central quantity to study. Its Wigner or phase space representation brings us close to classical concepts. In fact the less demanded above is classical

The various possible macro approaches can be nicely brought into a systematic perspective, Fig. 2. According to the duration of the process τ relative to the relevant micro to macro time scales τ_{int} , τ_{rel} , τ_{eq} of the duration of individual NN collisions, the local equilibration time and the global equilibration time respectively, one enters different macro regimes. As soon as many-body correlations have decayed (i.e. their influence on the one-body density effectively ceased) ($\tau \approx \tau_{\text{rel}}$) we enter the kinetic regime. The respective kinetic equation of the one-body density $f(r, p)$ is governed by a collision term besides the usual streaming (Vlasov) part.

(Markovian) accounting for two body collisions. Thus, its application is limited to the dilute gas regime. Later on when near local equilibrium is established ($\tau > \tau_{rel}$) one enters the hydrodynamical regime, the respective dynamical equations emerging from a moment expansion in momentum space of the kinetic equations.

In order to elucidate the micro preequilibrium phase, quite a variety of simplified models have been suggested and studied⁶⁾.

In order to elucidate the micro preequilibrium phase, quite a variety of simplified models have been suggested and studied⁶⁾. Guided by high energy pictures most of them employ straight line communication assumption in order to separate geometrical from dynamical effects. The transition from the quasi-free scattering of two nucleons out of their respective Fermi-seas (knock-out)⁷⁾ over many collisions towards the formation of a local equilibrium⁸⁾ has been studied. Within the frame of classical transport, as Markovian processes in time or in the number of collisions of individual constituents, they studied the amount of equilibration attained during the reaction as far as the kinetic and/or the chemical degrees of freedom

Fig. 2: Systematics of the different dynamical regimes

(pion production, formation of composite nuclei) are concerned.

As a result of these studies a nucleon loses its memory on its incident oriented motion after about 3 collisions; at low energies (0.1 - 0.5 GeV/u) due to the near isotropy of the NN cross section, at higher energies due to the onset of inelastic channels in the basic NN process. Hence, $\tau_{rel} \approx 6\text{fm}/v$ where v is the relative velocity of the two nuclei. To be more precise, at $\tau = \tau_{rel}$, those nucleons that were in interaction contact (c.f. the linked cluster picture discussed in ref. 9.1) attain a single particle spectrum that is close to a statistical equilibrium if averaged over many cascade events. This may not yet justify a hydrodynamical regime where in each event local equilibrium is required. The question under which circumstances the cascade shows hydrodynamical features is still not settled, c.f. however ref. 9.2). As for the present experience with realistic nuclear dimensions the hydro regime seems not yet reached.

Projected to the ultra relativistic regime, the picture will change. The proton-proton interactions being forward peaked will not be able to provide the equilibration of the kinetic degrees of freedom within the limited number of collisions that are possible. In addition the finite hadron formation time will prevent cascading effects, so that a certain transparency sets in, a picture that Anisethy et al. 10) have used to estimate the energy deposition in the fragmentation region.

III. The micro dynamical regime

The CEM and the INC models in connection with simplified multiple collisions approaches are the tools to study the evolution on the micro scale. While the initial effort concentrated on calculating inclusive spectra, fig. 3, by now some efforts were successful to bring more transparency into these complicated codes. Interesting in this respect is an attempt to disentangle the cascade in terms of those subsets of nucleons (connected cluster analysis) that are connected by 'violent' collisions, c.f. 9.1). These clusters comprise the micro dynamics of violent collisions that ultimately lead to micro equilibrium while the gentle collisions omitted in the analysis will govern the macro dynamics. A similar idea has been suggested by Bodmer et al. 4) for the analysis of the CEM approach in dividing the NN force into a long and short range part; the long range part governing the

Fig. 3: Some typical inclusive spectra from cascade calculations⁵⁾; left: calculation from J. Cugnon et al.; data ref. 17.2) right: calculation including statistical error bars from C. Noack, data (full lines) from ref. 17.1)

macro (collective) dynamics in terms of an averaged force (Vlasov part of the kinetic equation) while the short range force enters as a stochastic collision term. Given such a picture also the CEM calculations could be subjected to a corresponding cluster analysis. The main advantage of the cluster representation is that for one-body observables (i.e. inclusive cross sections) it brings us to formulation of the cross section as a sum over the single particle spectra pertaining to all possible clusters. This form is of the type that is most commonly employed in simple phenomenological approaches 6-8).

Ultimately such an analysis is an aid to reduce the inherent complexity of the intranuclear cascade description. In particular, the cluster decomposition may improve the practical utility of the INC for the study of relatively rare events, such as high-momentum components or multiparticle coincidences. As for the cluster analysis cited the main result is that already for small clusters with only 6 nucleons

or more the resulting one particle spectra have a quite equilibrated form with respect to the c.m. frame of each cluster. This motivated an interesting background study which I am going to explain next.

IV. The Nuclear Phasespace Model

The approved fast equilibration already on the micro scale, that is among a couple of nucleons only, stimulated a survey study of all the available inclusive data over a broad range of projectile/target combinations and of beam energies in terms of a phase space model: micro equilibration⁸⁾.

Assuming a limiting interaction contact among the nucleons (as explained above / or estimated from straight line communications) the phase-space model assumes (micro-) equilibrium distributions for the cluster spectra. In general we expect the one particle spectrum of the form

$$F_C(p_1) = \int \frac{d^3 p_2}{\epsilon_2} \dots \dots \frac{d^3 p_C}{\epsilon_C} \left| S(p_1, \dots, p_C) \right|^2 \delta \left(\sum_i p_i - P_C \right)$$

where P_C is the incident four momentum of the cluster $\{c\}$ and $|S|^2$ describes the exclusive probability for the final state $\{p_1 \dots p_C\}$. As the S-matrix cannot be obtained from first principles at this time, one follows Fermi's statistical theory⁸⁾ and assumes the least, which is the most chaotic possible: the equal opportunity employment of all accessible final states. Thus $S = \text{const.}$ and F_C only governed by the conservation laws, acquires the so called phase-space distribution. The intrinsic nuclear Fermi motion is included by a folding procedure over the incidentally available four momentum P_C of each cluster. Note, that opposed to thermal models which employ Maxwell-Boltzmanns law, these distributions explicitly take care of finite particle-number effects and thereby account for the finiteness of the available phase space. This leads to a significant change of the momentum distributions at large momenta, Fig. 4, and is the main reason for the relative success of the model. A collection of results for proton and pion inclusive data is given in fig. 5. For the fairness, in order to regulate the pion production rates, one parameter has been introduced into the theory. Else the form of the spectra follow from the assumption of kinetic equilibrium.

Fig. 4: Phase space distribution for different ensemble sizes $M+N=2, 4, 6, 16, \infty$ at fixed c.m. energy per nucleon.

Fig. 5: Phase space model calculations full line of Proton and Pion inclusive cross sections compared to data from ref's 17.2 - 17.7). The histogram in the 1GeV p+C case results from a cascade calculation^{11.5)}.

Despite of the success this simple model has microscopically seen, there are still open questions. In particular the spectra at large forward/backward momenta¹¹⁾; do we understand them to be built up by a sequence of binary on-shell collisions? Cascade estimates say no, Fig. 5 (c.f. ref. 11.5), and therefore draw attention to off-shell effects, i.e. genuine cooperative phenomena. Also for the production of pions at energies/nuc1 far below the NN threshold we see indications for cooperative effects, i.e. the common share of many nucleons is required to create a pion.

In summary of this section we see that for the inclusive spectra of the light systems so far investigated the micro-equilibrium assumption leads to a good reproduction of the moderate to energetic components. The agreement is better than a factor two. Is it, that physical effects have to be traced within this factor two departure from the phase space model or is it even such that the occurrence of micro equilibration distributions is already an interesting effect that should be understood more microscopically?

V. Search for collective flow effects

So far we discussed the micro regime of the dynamical evolution and its implications in particular on the energetic components of inclusive spectra. If the reaction has time to establish local equilibrium one enters a new regime, that of collective dynamics. The question we are faced is, by which observations we may isolate such collective effects, as for instance accommodated by hydrodynamical models (NHD), c.f. ref. 12). The dynamical pictures discussed are those of shock-waves, 'bounce-off' and 'side-splash' effects due to the central pressure built up. The physical phenomena expected are a sensitivity of the observables on the equation of state in general and the possible formation of density-isomers, pion condensates or ultimately quark matter, the topic of this workshop, in particular.

Compared to the observational capability in the macro world, where in each micro second millions of photons are lifting the secret of the space-time evolution of the object observed like the beauty of a milk drop's splash, Fig. 6, the experimental devices at our disposal for nuclear reactions are rather poor: a collection of ejectiles observed

SPLASH OF A MILK DROP

Fig. 6: Collective dynamics: above: Splash of a milk drop; Emulsion event; below: angular distribution of protons at lab momenta from 150 to 625 MeV/c for two multiplicity selections m_c , data from ref. 17.8); snapshots of a Ne+U reaction at 6 fm impact parameter in the hydrodynamical and the cascade model¹, from H. Stöcker

at certain asymptotic momenta. Clearly, to come closer to the secrets of the nuclear world, we rely on our imagination and a lot of theoretical experience with various kinds of models.

Our present experience tells us that inclusive measurements of a single ejectile do not suffice. Most of the structural differences are washed out as only one particle is observed from each event and due to the average over all impact parameters. In particular if one is interested in collective flow effects that result from the response on the high compression we have to discard peripheral collisions where we believe that non equilibrium cascading processes are prevailing. In fact, recently observed proton spectra associated with high multiplicities in 400 MeV/u on U show a slight forward suppression in the emission, Fig. 6, an effect that has not yet been explained by the INC while the NHD model shows similar features^{12,13}. Although there are still many effects to be considered such as Coulomb, formation of composites ... that may perturb the spectra at these low ejectile energies, we have at least a signal!

As we have not yet really a decisive clue one may ask: is there a near model-independent way to isolate collective flow effects from the asymptotically observed momenta, my tentative answer is: yes! As the collective flow is a genuine many-body effect we have to exploit many-body observables, the idea being similar to those used in particle physics for the identification of jets in terms of thrust or sphericity¹³. Our situation, however, is more subtle because of the near random appearance of our high multiplicity events. It is clear that if we want to isolate collective flow effects we have to look for bulk properties of the emission pattern. Any high energy ejectile results from fluctuations on the micro scale (as discussed above) and not from a certain preferred direction of the macro flow. Thus any confirmation of a collective flow-effect and its possible sensitivity on certain physical effects can be found at best in the study of a few lowest moments of the asymptotic observables.

Suppose for each event we know all momenta $\vec{p}^i$ of a certain number of emitted particles (the more of them, the better). Relative to their c.m. frame one can construct the respective second rank momentum tensor

$$Q_{ij} = \frac{1}{N} \sum_i \vec{p}_i^j \sum_j \vec{p}_j^i \quad i, j = \{x, y, z\}$$

where $\gamma(P)$ is a suitably chosen scalar measure. While thrust is only capable of isolating one preferred emission axis the above second rank tensor has the distinct advantage that it represents already the global shape structure for each event. In fact Q_{ij} represents an ellipsoid and through diagonalisation one can express its contents by its three major axis $\{\vec{q}_1, \vec{q}_2, \vec{q}_3\}$ with $q_1 < q_2 < q_3$. Inserting the relative length of the major axis

$$\lambda_i = q_i / \sum_{i=1}^3 q_i$$

into a Dalitz kind of triangular plot opens the possibility for a shape analysis. The sphericity $S = \frac{3}{2} (\lambda_1 + \lambda_2)$, for example, is a scalar measure with isotropic events if $S=1$ and pencil like events if $S=0$.

There are certainly many ways to represent the shape structure in terms of the tensor Q_{ij} . For a first survey we chose a representation that directly shows the direction of the preferred emission and the amount of elongation $\varepsilon = 1-S$ in that direction. Thus we represented it by one vector $\vec{\varepsilon} = (1-S) \hat{q}_3$. It explores the inside of a unit sphere, with isotropic events for $\vec{\varepsilon}=0$ and pencil like events at its periphery ($|\vec{\varepsilon}|=1$). This vector is precisely of the desired kind (a low moment) and has the ability to isolate the occurrence of collective flow effects. Thus, 'elongation' cross sections $d^3\sigma/d^3\varepsilon$ taken for a certain but high multiplicity range may contain the clue. Such cross sections as obtained from a cascade analysis are displayed in form of a contour plot over the elongation plane $(\varepsilon_u, \varepsilon_v)$, in fig. 7. While at 360 MeV/u the resulting events show near isotropic emission patterns ($\varepsilon=0$) with a slight preferential elongation in beam direction there is a strong elongation in beam direction of $\langle \varepsilon^2 \rangle / 2 \langle \varepsilon^2 \rangle \approx 1.6$ at 1.2 GeV/u. Besides fluctuations due to finite particle number effects (low multiplicities have larger fluctuations) this finding appears to be independent of the multiplicity. Thus cascade makes a strong prediction. Irrespective of the type of event (peripheral or central) the global shape of the resulting participant pattern is about the same and carries the memory of the incident beam direction. Within the accuracy dictated by the fluctuations the predictions of a hydrodynamical scenario shows in fact a different expectation, c.f. the dashed (ridge) line which results from transcribing the result of H. Stöcker^{13,7} into this plot.

Fig. 7: Distribution of cascade events (counting only participants) over the elongation plane $\vec{e} = (e_x, e_y, e_z)$; parallel denoting the beam directions. The contour lines separate a factor of two, respectively. Isotropic events at $\vec{e} = 0$; pencil like events at $|\vec{e}| = 1$. Calculations from ref. 13.9. Dashed line: ridge line of the hydrodynamical model at impact parameters from 0 to 6 fm.

Finite particle number fluctuations have not yet been included into the hydrodynamical calculations. The importance of these fluctuations has been first discussed in ref. 13.5).

In conclusion, with the heavier beams and the new 4π multiparticle detecting devices in the near future, I see the fascinating possibility to clarify the existence of collective flow effects in such reactions.

VI. The Nucleisation Process

So far we discussed that phase of the reaction where the matter involved could be considered as a continuous medium: the 'fluid' of hot and dense nuclear matter. Ultimately the system expands, and it has to break-up to isolated nuclei (and hadrons at higher energies), a process that in analogy to the hadronisation process in high-energy reactions I like to call NUCLEISATION. It is this disassembling process, that so far is the most crudely described and understood part of the reaction. It sensitively governs the production of composite particles like deuterons or alpha particles, an interesting perspective in particular for the new energy regime below 100 MeV/nucleon.

It is clear that this process is essentially governed by quantum effects. Yet, with the exception of one approach given by Remler¹⁴⁾ all other models use quite classical concepts like the coalescence picture¹⁴⁾ or the chemical equilibrium⁸⁾. The latter ones certainly provide a systematic survey, however, they are not at the level as to allow quantitative predictions. In this respect Siemens and Kapusta¹⁵⁾ suggested a very controversial though stimulating idea: to deduce the entropy attained during the reaction from the observed rates of deuterons to protons. Their reasoning, however, was based on the assumption of a chemical equilibrium between nucleons and deuterons at least at the late stage of the reaction. This way they deduced entropies that exceeded by two units the expectations from conventional models which implies a factor of 10 in the d/p ratio! Fig. 8. By now many suggestions were made to solve this puzzle. They all essentially criticize the chemical equilibrium picture employed¹⁵⁾: a) the formation and decay of heavier metastable compounds (H. Stöcker), non equilibrium effects (T. Biro et al.) and c) quenching effects: either through an excluded volume (T. Biro et al.) or through the Pauli exclusion¹⁶⁾. The latter effect is known in plasma physics as a Mott transition. The picture is, that the surrounding matter alters the effective binding forces of the compounds to such an extent that their bound states emerge into the continuum. Thus no compounds exist beyond a critical density. While the present estimates are still low density corrections to the simple detailed balance law of mass action they already suggest a saturation in the concentration of deuterons as a function of the density of the system, with d/p ratios close to the

Fig. 8: Deuteron/Proton ratio: data c.f. ref. 17.9), hatched area: expectation from conventional models on the basis of the chemical equilibrium assumption; full line: decay of meta stable compounds, H. Stocker¹⁵⁾; dashed line: upper limit in the quantum statistical picture (c.f. fig. 9)

Fig. 9: Percentage of protons appearing as free protons or bound into deuterons and higher compounds as a function of the density ρ of the system at $T=40$ MeV. LMA: law of mass action; QS: quantum treatment with Pauli quenching, Knoll et al.¹⁵⁾.

observed ones, Fig. 9.

Altogether it seems reasonable that static equilibrium concepts - if they make at all sense for such dynamical processes - are only reasonable if they are not used in the simple low density (non interacting gas) limit but rather have included some medium corrections as discussed above or by considering the next virial coefficients in the expansion (Jennings et al.¹⁵⁾).

With respect to the importance of quantum effects there is an interesting new approach to calculate the formation of composite particles given by Remler¹⁵⁾. Starting from a T-matrix description of the process, e.g. deuteron production, and casting it into a Wigner-phase space representation they obtain an expression where the exact two particle Wigner function of the system is examined with respect to its overlap with the final state deuteron Wigner function. The essential approximation employed is to replace the exact two particle Wigner function by the classical two particle phase-space distribution obtained from a cascade calculation. As to their result, it is essentially in the last collision where the decision is made, whether a nucleon together with a near neighbour can form a deuteron. First results with this technique seem to give promising results for the deuteron production even for cases where the classical concepts above have failed (Gyulassy et al.¹⁵⁾).

Conclusion

In summary, I discussed various aspects of the collision dynamics of nuclear reactions in the BEVALAC energy range: from the micro to the macro dynamics. While a signature of the micro dynamics seems to be best seen in the high momentum components of the emitted particles, macro-collective effects essentially coin the moderate to low momentum components.

We saw signs that both the high longitudinal and transverse momenta preferentially result from a cooperative action of a couple (≈ 4) of nucleons. Whether this is due to initial state correlation or multiple scattering, whether it happens coherently or incoherently is not yet settled. Further measurements, in particular coincidences of these rare components with other ejectiles, may help to clarify the reaction dynamics. As for the pion spectra, they also show strong signs of

kinetic equilibration. There is not yet a clear signature on the role of the delta resonance and better π^+ , π^- data in the mid-rapidity region are necessary to settle this problem, besides the role of Coulomb effects. Further, the relatively strong pion production at 'subthreshold' energies deserves our future attention as it clearly may point towards cooperative effects.

With the entropy puzzle boosted, a growing interest to understand the production of composite particles could be recorded over the last two years. Here I see a promising perspective for those types of approaches that evaluate quantum formulations of the respective cross sections with quasi-classical approximants.

As for the search for collective effects, hydrodynamical pictures suggested quite a variety of phenomena. On the other hand cascade calculations made quite different predictions for the emission patterns. Therefore with the new beams up to heavy nuclei and the new 4π multi-particle detecting devices I see a challenging perspective to settle some of the questions concerning the macro dynamics. From there, however, to some detailed statements about the behaviour of nuclear matter under extreme conditions there is still a long path to go.

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