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Reactions

Energetic Particles Emitted from Energetic Nuclear

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Abstract:

The abstract is not clearly visible due to the image quality. It appears to discuss the necessity of off-shell scattering effects in the context of nuclear reactions, possibly involving the deexcitation of nuclei and the implications of a simple phenomenological model. The focus seems to be on the role of off-shell scattering in understanding specific nuclear reactions, possibly within the framework of a theoretical or computational model.

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Reaction products emitted with high momenta have been of continuous
interest in the study of energetic nuclear reactions. The first proton backward
production data [1] with momentum transfers of 2 GeV/c simulated quite a va-
riety of explanations. Single scattering models link these observations to
the high momentum components of the intrinsic nuclear motion, i.e. Fermi
motion [2]. On the other hand, multiple collision contributions as well as ini-
tial state correlations also open the extremes of phase space. Some models,
for example, assume that the incident particle hits a region of accidentally
increased density (fluctua or correlated cluster [3]). Thus, given a multi-
ple collision picture, nucleons exhibit quite different spectral patterns
according to their respective fate (fig. 1):
- spectators contributions from nucleons which have not suffered any energetic
collision. This part mainly reflects the intrinsic nuclear momentum distribu-
tion (Fermi motion);
- quasi-free scattering contributions of nucleons scattered out of their re-
spective Fermi seas by a single collision (knock-out, hard scattering [4]);
and
- multiple collision contributions, nucleons that have scattered more than
once. They populate a relatively broad region in momentum space up to the
kinematical limits.
Thus concentrating on the extreme momentum components (hatched area in fig.
1) we are faced with the question which of the above alternatives is the dom-
inant mechanism.

In the past only a limited body of data has been discussed in either of
these pictures [1-4]. Yet, in order to attain a convincing support for the
dominance of one of these alternatives a systematic study over a broad range
in beam energies and projectile/target combinations is necessary. It is the
aim of this note to present such a survey for proton and pion spectra by means of
a model that supports the multiple collision perspective, the nuclear
phase space model [5]. This way we concentrate on the participants only, ig-
noring the fate of the spectators. Alongside, in order to ascertain the
importance of off-shell scattering effects we also include calculations in a
simplified cascade picture, the linear cascade model, as described in detail
in ref. [6]. Note that a full scale multiple collision model like the intra
nuclear cascade model would not be able to predict precise cross sections in
the extreme parts of the spectra even with a factor hundred more in computing
time than currently used. Thus, we rely on phenomenological studies.

Clearly in a regime where the NN cross section is fairly isotropic, the
most essential property of multiple collisions is to open the accessible
phase space (fig. 1). The more nucleons know from each other through in-
teractions the larger their accessible phase space. In a diagramatic language:
the connectedness of the diagramm that describes the process is crucial.
This introduces the notion of linked clusters. As a consequence, one-body observables like the single inclusive cross section to observe a specific
particle τ can be built up by an incoherent sum over all possible linked
clusters, for details we refer to ref.[7],

$$E_τ\frac{d^4σ}{dp_τ^3} = \sum_{(M,N)} \sigma_{AB}(M,N) F^τ_{MN}(P_τ).$$

(1)

Here each contributing cluster (M,N) is classified according the numbers N
and N of nucleons which originate from the projectile A and target B, respect-
ively. Besides Fermi motion these labels entirely determine the kinematical
input in form of the total energy and momentum. If interested in the trend of
the cross section over several orders of magnitude it is important to have
much more precise knowledge of the spectral form, $F^τ_{MN}(P_τ)$, than on the forma-
tion cross sections $σ_{AB}(M,N)$ (a convincing argument is given by fig. 4,
discussed below). Therefore we take the latter ones from the straight-line
estimate [8,6]. This leaves us to discuss the momentum distributions $F^τ_{MN}(P_τ)$

In the limit of maximum ignorance of the dynamics we can estimate these
spectra from the density of final states, i.e. phase space. Considering only
nucleons and pions in the final state, we employ the nuclear phase space
model in precisely the version of ref [5], except for one refinement. It con-
cerns the only free parameter of the model: the critical density $ρ_c$ which
governs the pion production rates. The energy independent choice of $ρ_c$
as used in ref [5] was not be able to reproduce the observed beam-energy dependence
of the $τ$-multiplicities (c.f. fig. 2 of ref [5]). We therefore take it as a
function of the c.m. energy per nucleon vs available to each cluster in such
a way that presently available pion multiplicity data [9] are fitted by the
model. This choice is at least in line with the observation that the multi-
the high momentum parts of the spectrum are quantitatively reproduced by the model. Although we do not expect a good reproduction of the low energy parts by the model, since a lot of unconsidered effects like Coulomb and binding effects set in, we do also have to mention that the low energy part of these data have been criticized. Recent measurements at 80 MeV/nuc. [19] show a steady increase of the cross section towards lower proton energies, so that the actual discrepancy between prediction and observation will turn out much less than given by fig. 6.

For the pions produced the model reproduces the shapes of the spectra with comparable quality, fig. 7. In view of the extrapolation of the production rates down from high energies also the absolute rates appear not too bad. Recently pion data have been measured in the threshold regime. They show a remarkable target mass scaling, i.e. the data are hardly sensitive to the target mass if plotted versus Feynman's scaling variable $x_Q$. Fig. 8 demonstrates that this behaviour appears as a simple consequence of the available phase space. This phenomenon persists up to higher projectile energies, as a replottting of the data of Papp et al. [17] together with our model calculation shows.

Finally, fig. 9 shows that for pion production our statistical model gives reasonable predictions even at very low bombarding energies. Of course the absolute magnitude of the cross section is not that good, yet in view of the extrapolation of the rate parameter $\rho$, that has been made it is more than an educated guess. Actually, tuning of $\rho$'s always gives absolute magnitude of the spectra without severely altering the shape. We therefore give a prediction for the experiments currently under preparation at CERN in the same figure; preliminary data [20] already give a support of the quality of our guess.

In summary, it has been shown that a simple model which incorporates -the mutual interaction of several (but generally a few) nucleon; -the even occupation of phase space by these nucleons (and particles eventually produced by them) at the end of the reaction i.e. a model that accommodates multiple collision contributions in the phase space limit is able to explain an enormous body of inclusive data from energetic nuclear reactions. The model, to repeat, does not apply specific re-

action dynamics. It gives the phase space limit as the ultimate limit of all possible reaction pictures. This is a quite serious but intended restriction. In the sense of a surprisal analysis the presented success of the model may help clarifying the information content of the measurement and thus may help identifying the actual reaction mechanism. As for the pion data analysed, we see the absolute production rate as the primary quantity that is measured by these data. The cascade analysis performed alongside clarified that a sequence of binary on-shell NN collisions was not able to access the discussed extreme areas of phase space. Rather, the data ask for a cooperative action of many nucleons (off-shell scattering / effective many body forces), encouraging further studies in this direction especially correlation studies.

References

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Figure 2) The dependence of $P_C$ on the kinetic c.m.-energy per nucleon $\sqrt{s}-m_0$ available to each cluster. Circles: $P_C$ values required to reproduce the observed multiplicities at individual beam energies in the range 0.36 to 2 GeV/nucleon [9]. Line: polynomial fit as used for the extrapolation to low energies.

Figure 3) Transverse slopes of the proton and pion spectra illustrating the effect of the energy dependence of $P_C$. Data from ref [13].

Figure 4) Forward cross section ($0^\circ$ relative to the projectile frame or backward cross section ($180^\circ$ relative to the target frame) decomposed with respect to the sizes $M+N$ of the different contributing cluster. $I$ denotes the sum of all contributions.

Figure 5) Forward/backward yield of protons in the energy range of 0.09 to 2 GeV/nucleon for various projectile/target combinations. Data from ref's [14]. Full lines: results of the phase space model; the histogram in the right figure: result of the on-shell cascade dynamics for the proton induced reaction.

Figure 6) Proton yield at 86 MeV/nucleon beam energy as a function of laboratory angle and energies. Data from ref [15]. Full lines: phase space model.
Figure 9: Subthreshold pion production at 80 and 86 GeV/nucleon. Data from

Data from ref. [16].

Figure 17: p<sup>-</sup> production at 200 GeV/nucleon.

Figure 18: p<sup>0</sup> production at 200 GeV/nucleon.