Energetic Particles Emitted from Energetic Nuclear Reactions*

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Protons and pions emitted with extreme momenta from energetic proton and heavy ion induced nuclear reactions are analysed in terms of two simple phenomenological models: the nuclear phase space model and a simplified multiple collision model. The systematic analysis of the observed spectra over many orders of magnitude for a variety of projectile and target combinations in the beam-energy range of 0.08 to 2 GeV/nucleon shows the importance of multiple collision contributions and the necessity of off-shell scattering effects.

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 stimulated quite a variety 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 initial 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 (fluctuation or correlated cluster [3]). Thus, given a multiple collision picture, nucleons exhibit quite different spectral patterns according to their respective fate (Fig. 1):

- spectator contributions from nucleons which have not suffered any energetic collision. This part mainly reflects the intrinsic nuclear momentum distribution (Fermi motion);

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Fig. 1. Illustration of the various contributions to the inclusive spectrum as a contour diagram over the momentum plane (i denoting the direction of the beam); a) the Fermi motion of the nucleons in the incident nuclei (the decay of the spectators gives rise to a spectrum of this type); b) quasi-free scattering of two nucleons out of their Fermi seas (knock-out); and c) spectrum from multiple collisions. The hatched areas are the ones of interest.
- quasi-free scattering contributions of nucleons scattered out of their respective 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 dominant 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 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, ignoring 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 [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 interactions the larger their accessible phase space. In a diagramatic language: the connectedness of the diagram that describes the process is crucial. This introduces the notion of linked clusters. As a consequence, one-body observables likes the single inclusive cross section to observe a specific particle $\tau$ can be built up by an incoherent sum over all possible linked clusters (for details we refer to Ref. 7)

$$E_\tau d^3p_\tau^3 = \sum_{(M,N)} \sigma_{AB}(M,N) F_{MN}(p).$$

(1)

Here each contributing cluster $\{M,N\}$ is classified according to the numbers $M$ and $N$ of nucleons which originate from the projectile $A$ and target $B$, respectively. Besides Fermi motion these labels entirely determine the kinematical input in term of the total energy and momentum. For the trend of the cross section over several orders of magnitude it is more important to have precise knowledge of the spectral form, $F_{MN}(p)$, than of the formation cross sections $\sigma_{AB}(M,N)$ (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 $F_{MN}(p)$.

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 [5], except for one refinement. It concerns the only free parameter of the model: the critical density $\rho_c$ which governs the pion production rates. The energy independent choice of $\rho_c$ as used in [5] was not able to reproduce the observed beam-energy dependence of the $\pi$-multiplicities (cf. Fig. 2 of [5]). We therefore take it as a function of the c.m. energy per nucleon $\sqrt{s}$ 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 multiplicity of pions relative to the multiplicity of participant nucleons is approximately a function of the beam energy per nucleon only and not of the projectile/target combination. In this way the pion rates are adjusted and extrapolated into the unknown regime below 400 MeV/nucleon while the spectral shapes emerge from the equal opportunity assumption of the model. Although the above modification allows us to predict absolute cross sections without any further adjustable parameter, it also reflects our present ignorance of the actual pion production mechanism.

The energy dependence of $\rho_c$ is shown in Fig. 2. It is evident from the strong energy dependence and in particular the rather high values of $\rho_c$ required at

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