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A.H. BLIN, S. BOHRMANN, J. KNOLL

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Planckstr. 1 · Postfach 110541 · D-6100 Darmstadt 11 · Germany

ENERGETIC PARTICLES EMITTED FROM ENERGETIC NUCLEAR REACTIONS[+]

Alex H. Blin[*]
Max-Planck Institut für Kernphysik, D6900 Heidelberg, Germany

Steffen Bohrmann[**]
Nuclear Science Div., Lawrence Berkeley Laboratory, Berkeley CA 94720

Jörn Knoll
Gesellschaft für Schwerionenforschung, D6100 Darmstadt, Germany

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* Present address: Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742;

** Present address: Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 19, 6900 Heidelberg, Germany.

Abstract:

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/nucl. shows the importance of multiple collision contributions and the neccessity of off-shell scattering effects.

Reaction products emitted with high momenta have been of continuous interest in the study of energetic nuclear ractions. 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 (fluctuon 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 enegetic collision. This part mainly reflects the intrinsic nucler momentum distribution (Fermi motion);
- *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 the dominance of one of these alternatives a systematic study over a broad range in beam energies and projectile/target combinations is neccessary. 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 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 isotopic, 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 accesssible 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],

$$E_\tau \, d^3\sigma/dp_\tau{}^3 \;=\; \sum_{\{M,N\}} \sigma_{AB}(M,N)\, F^{\tau}_{MN}(\, p_\tau). \tag{1}$$

Here each contributing cluster {M,N} is classified according 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 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, $F_{MN}(p)$, than on 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 ref [5], exept for one refinement. It concerns 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 able to reproduce the observed beam-energy dependence of the π-multiplicities (c.f. fig. 2 of ref [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/nucl. while the spectral shapes emerge from the equal opportunity assumption of the model. Although the above modifcation allows us to predict absulute cross sections without any further adjustable parameter, it also reflects our present ignorance of the actual production mechanism.

The energy dependence of ρ_c is shown in fig. 2. It is evident from the strong energy dependence and in particular the rather high values of ρ_c required at high energies, that the common interpretation of ρ_c as a ***freeze-out density*** of a system in ***chemical equilibrium*** [10] makes little sence. Rather, in the context of ***Fermi's*** theory [11] we view ρ_c as an implicite parametrisation of the pion production S-matrix.

One of the subtle consequences of the energy dependence of ρ_c is the difference in slopes that now emerges for the transverse pion and proton spectra, fig. 3. This is due to the fact, that even for a fixed beam energy there is a spread in c.m. energies for the various contributing clusters {M,N}.

Given the employed picture where ***all participants*** of a reaction group into several ***small clusters*** where each cluster comprises all the ***dynamically dependent*** particles, one may ask: which cluster type {M,N} gives the most significant contribution in which area of phase space. For the forward (backward) yield of protons in a 1 GeV/nucl. heavy ion collision this question is analysed in fig. 4. The result is qualitatively the same at other energies and also for the pion spectra. Note that due to the Gaussian shaped Fermi-momentum distributions employed the quasi-free scattering contribution ($M = N = 1$) drops off quite significantly. Rather, the most eminent cross section at high momenta results from processes where about 4 nucleons participate. Thereby the preferred ratio of projectile to target matter in each cluster M/N follows from kinematical considerations: $M/N>1, \simeq 1$ or <1 for forward, sideward or backward emission, respectively. Note further the observed fragmentation peak at $p=0$ which has a width reflecting the Fermi motion of the projectile [12]. In our picture this peak results from the decay of the

projectile fragment (i.e. spectator) with a spectrum as in fig 1a and is therefore not included in our phase space description. The participant part, however, is very well reproduced by our model. This holds for quite a variety of projectile/target combinations as well as for a broad range in beam energies from 80 MeV to 2 GeV/nucl.(fig.5). Concerning the trend with energy one may draw the conclusion that for the light systems so far observed a kind of transparency sets in above 1 GeV/nucl.: experimental slopes saturate while the model spectra steadily broaden with increasing bombarding energy. Obviously no longer all but a fraction of the available energy is transformed into ***heat***. The remarkable insensitivity of the measured spectral shapes even up to beam energies of 400 GeV seems to demonstrate a saturation in the deposited energy.

One interesting question to ask is which are the dynamical mechnisms that open these extreme areas of phase space. In particular, one likes to know whether a sequence of ***binary on-shell*** scattering processes is able to do it. For this discussion we concentrate on proton induced reactions as the reaction dynamics is much simpler. There the projectile nucleon has the chance to scatter off N target nucleons through a sequence of binary collisions. Enforcing on-shell dynamics on each micro collision we culculated the spectral shapes $F_{1N}(p)$ for the emitted protons (c.f. eq.(1)). Applying the same weighting factors $\sigma_{pB}(1,N)$ as in the phase space model results in a spectrum that is shown in the histogram in fig.5. This Monte Carlo calculation compiles half a million runs which with with the bin size chosen leads to a noise level of about 0.1 to 1 mb/GeV² for the displayed cross section. Although accessible through phase space considerations we do observe a sizeable depletion at high momenta. The yield integrated for all momenta above 400 MeV/c is seen to miss an order of magnitude relative to the data. Even accounting for a possible subsequent rescattering of struck target nucleons with cold target matter does not help filling the gap. We therefore conclude that processes other than binary on-shell scattering are neccessary to populate these regions of phase space. This pionts towards ***cooperative*** effects of a kind other than accounted for by ***cascade*** dynamics.

Returning to the BEVALAC energy regime we find a quite enormous range in beam energies over which the model gives appreciable predictions. This is supplemented by fig.6, where even for beam energies as low as 86 MeV/nucl.

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 critisised. Recent measurements at 80 MeV/nucl. [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_F. 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 replotting 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 ρ_c that has been made it is more than an educated guess. Actually, tuning of $\rho_c(s)$ cures the absolute magnitude of the spectra without severly 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) nucleons;
-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 accomodates 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 mesured 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), encuraging further studies in this direction especially correlation studies.

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FIGURES

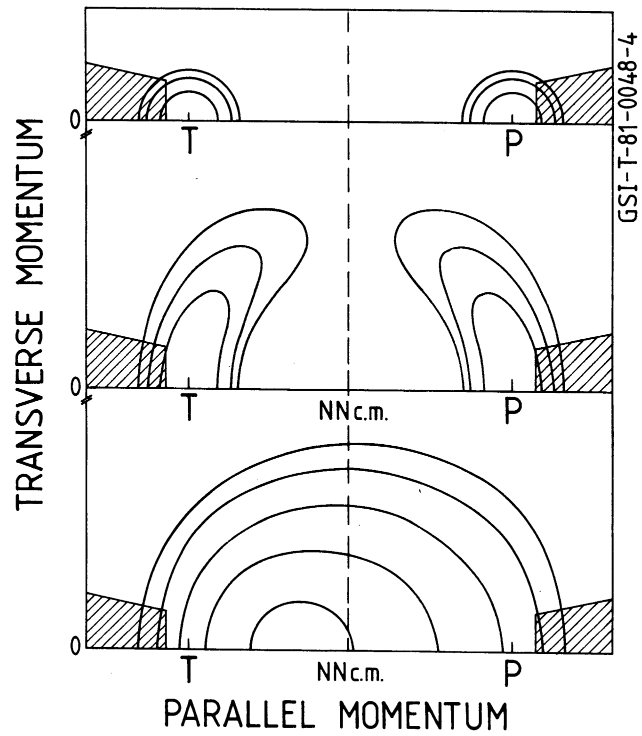


Figure 1) Illustration of the various contributions to the inclusive spectrum as a contour diagramm over the momentum plane (‖ denoting the direction of the beam); a) the Fermi motion of the nucleons in the incident nuclei, the decay of the spectators gives rise to a spectrum of this type; b) quasi-free 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.

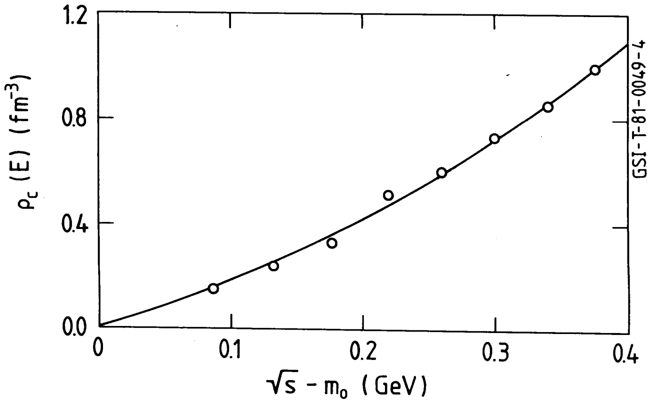
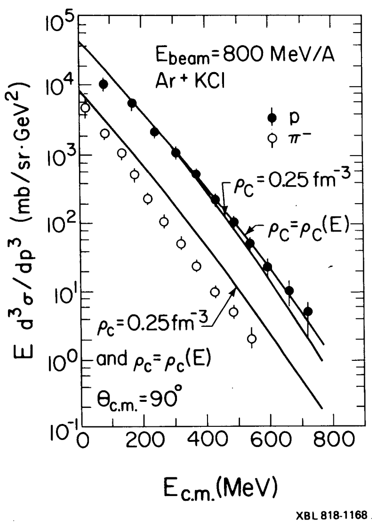


Figure 2) The dependence of ρ_c on the kinetic c.m.-energy per nucleon $\sqrt{s}-m_0$ available to each cluster. Circles: ρ_c values required to reproduce the observed multiplicities at individual beam energies in the range 0.36 to 2 GeV/nucl. [9]. Line: polynom fit as used for the extrapolation to low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



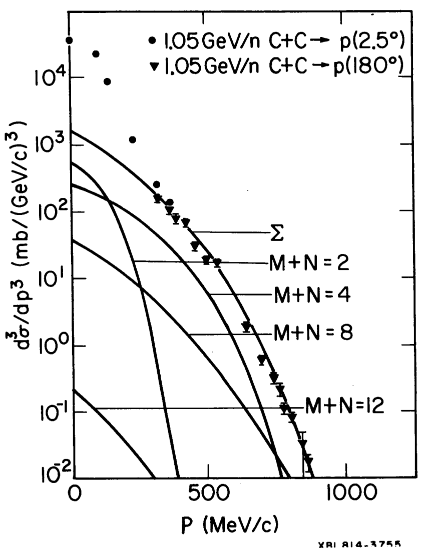


Figure 3) Transverse slopes of the proton and pion spectra illustrating the effect of the energy dependence of ρ_c. Data from ref [13].

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

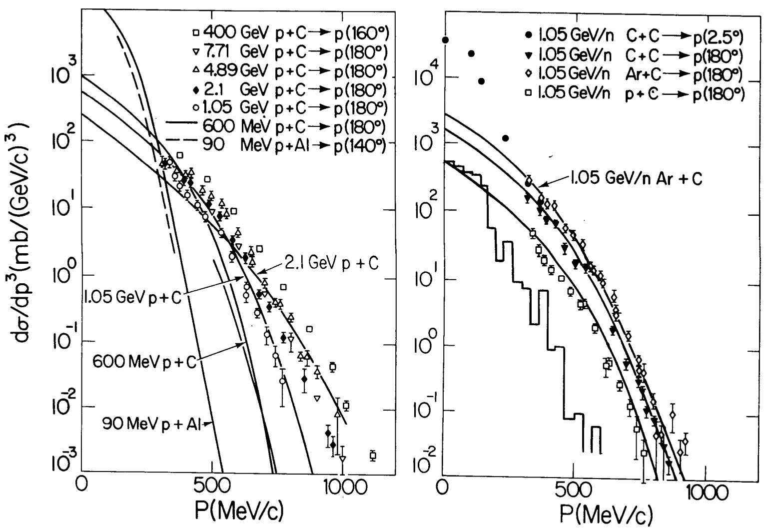


Figure 5) Forward/backward yield of protons in the energy range of 0.09 to 2 GeV/nucl. for various projectile/target combinations. Data from ref's [14]. Full lines: results of the phase space model; the histogram in the right figure: result of the on-shell cascade dynamics for the proton induced reaction.

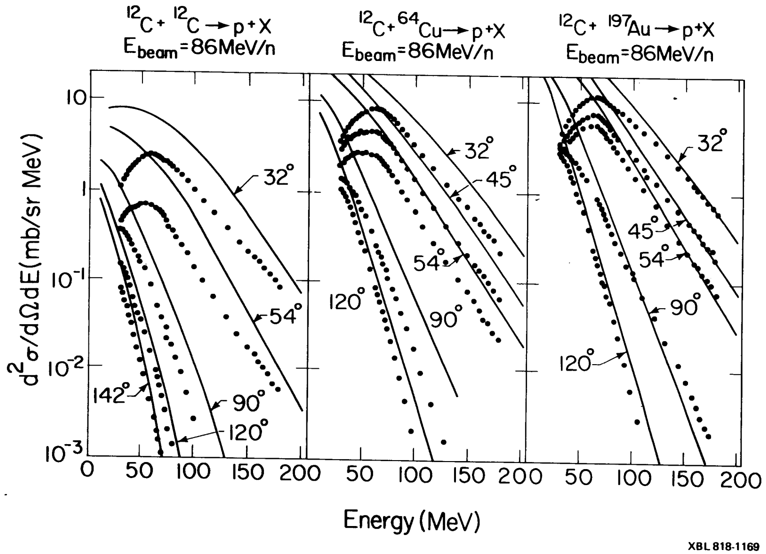


Figure 6) Proton yield at 86 MeV/nucl. beam energy as a function of laboratory angle and energies. Data from ref [15]. Full lines: phase space model.

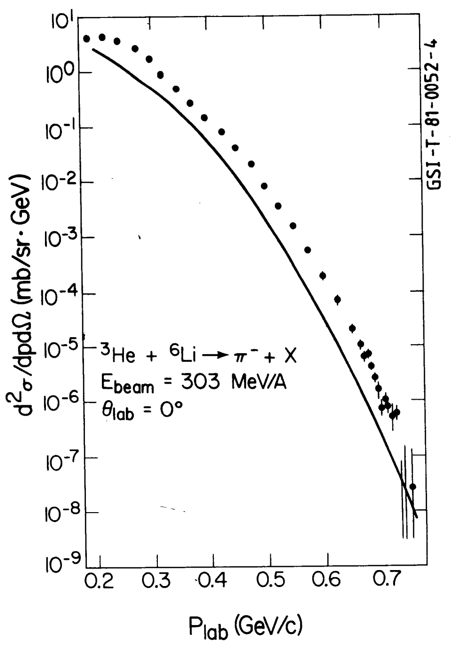


Figure 7) 0° - pion production up to the kinematical limit at 303 MeV/nucl.. Data from ref [16].

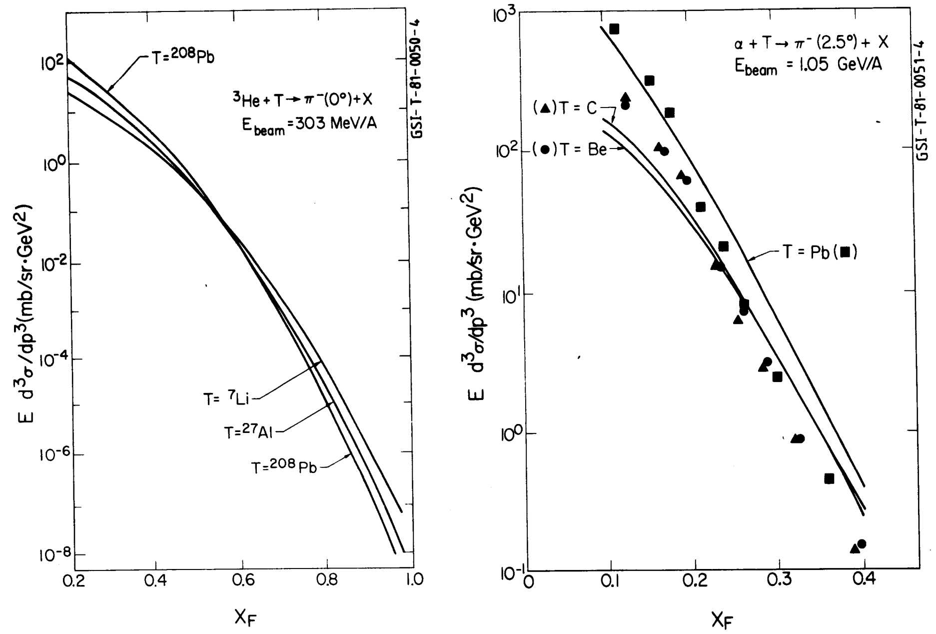


Figure 8) Forward pion production for different projectile/target combinations plotted against Feynman's scaling variable $x_F=(p_\pi/p_{\pi\ max})_{c.m.}$. Left part: at 303 MeV/nucl.; right part at 1.05 GeV/nucl.. Data from ref.[17].

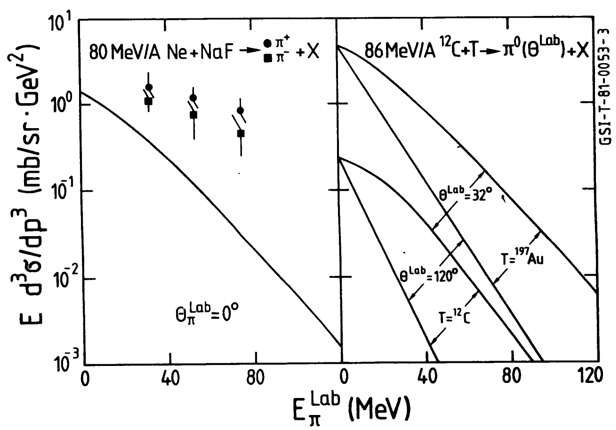


Figure 9) Subthreshold pion production at 80 and 86 MeV/nucl.. Data from ref. [18].