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Authors
Knoll, J.
Randrup, J.

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Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

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Jörn Knoll and Jørgen Randrup

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Proton-proton Correlations in High-Energy Nuclear Collisions*

Jörn Knoll+ and Jørgen Randrup

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720, U.S.A.

Abstract: Two-particle coincidence data are studied by the linear cascade model. In heavy-mass collision systems, the correlated contribution becomes obscured by an uncorrelated background. The height and the position of the quasi-elastic peak is sensitively influenced by the background term and by correlations due to the sharing of energy and momentum among more than two particles.

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+present address: Gesellschaft für Schwerionenforschung (GSI) Postfach 110541, D6100 Darmstadt, Germany.

After years of effort to understand one-particle inclusive cross sections in high-energy nuclear collisions, recent experimental[1-4)] and theoretical[5-8)] studies have concentrated on two-particle coincidence spectra. While the inclusive spectra allow a number of mutually conflicting interpretations, coincidence data are expected to be better suited for elucidating the collision dynamics. In this paper we study proton-proton correlations on the basis of a multiple-collision picture, which appears to us to provide the most appropriate framework for discussing genuine two-body correlations. However, full-scale cascade calculations[8] lack in transparency as well as precision (statistics). So, for the present exploratory study, we make use of a simplified multiple-collision approach where the geometrical aspects separate from those of the microscopic baryon-baryon dynamics: the linear cascade model 'rows on rows'[8,9)]. This model expresses the one- and two-particle spectra in terms of contributions from the various sub-groups of nucleons which have had violent interactions among themselves (clusters):

$$E \frac{d\sigma}{d\vec{p}} \equiv \sigma_{AB}(\vec{p}) = \sum_{MN} \sigma_{AB}(MN)\, F^{1}_{MN}(\vec{p}) \tag{1a}$$

$$E E' \frac{d^2\sigma}{d\vec{p}\, d\vec{p}\,'} \equiv \sigma_{AB}(\vec{p}\,\vec{p}\,') = \sum_{MN} \sigma_{AB}(MN)\, F^{2}_{MN}(\vec{p}\,\vec{p}\,') + \sum_{\substack{MN \\ M'N'}} \sigma_{AB}(MN\,M'N')\, F^{1}_{MN}(\vec{p})\, F^{1}_{M'N'}(\vec{p}\,') \tag{1b}$$

Here M and N denote the number of projectile and target constituents in each cluster (see ref. [9-12]), and E and $\vec{p}$ are the energy and momentum of the observed particles. We confine the study to participant nucleons only which implies M, N ≥ 1.

The model simplifications adopted in our study are the following: i) straight-line geometry estimates for the formation cross sections $\sigma_{AB}(\ldots.)$ (see refs. [1,6] and Appendix) and ii) given M and N a Monte Carlo simulation[10] of the sequence of binary collisions of each of the M projectile nucleons with each of the N target nucleons; see ref. [11] for details. The sampling of all events with one nucleon at momentum $\vec{p}$ or a pair of nucleons with momenta $\vec{p}$ and $\vec{p}'$ yields the spectral distributions $F^1_{MN}(p)$ and $F^2_{MN}(\vec{p},\vec{p}')$, respectively. It is clear that in nucleus-induced reactions (A > 1, B > 1) several clusters may be simultaneously present in the same event so that the two observed particles may originate from different clusters. This is expressed in an uncorrelated background term in (1b)

$$\sigma^{back}_{AB}(\vec{p}\,\vec{p}') = \sum_{\substack{MN \\ M'N'}} \sigma_{AB}(MNM'N')\, F^1_{MN}(\vec{p})\, F^1_{M'N'}(\vec{p}') \tag{2}$$

which vanishes in nucleon-induced reactions (A = 1). The physically interesting correlation part, where both nucleons emerge from the same cluster,

$$\sigma^{corr}_{AB}(\vec{p}\,\vec{p}') = \sum_{MN} \sigma_{AB}(MN)\, F^2_{MN}(\vec{p}\,\vec{p}') \tag{3}$$

may be split further into the knock-out component (M = N = 1)

$$\sigma^{KO}_{AB}(\vec{p}\,\vec{p}\,') = \sigma_{AB}(1,1)\;F_{11}(\vec{p}\,\vec{p}\,') \tag{4}$$

and the remaining correlated contribution from clusters containing more than two nucleons (M + N > 2).

Recent investigations have concentrated on isolating the knock-out component in order to study the quasi-free scattering in matter. In our model the various contributions are found to scale like

$$\begin{aligned}
& & & A = B \\
\sigma^{KO} &\approx A^{1/3} B^{1/3}\ 150\,\text{mb} & &= A^{2/3}\ 150\,\text{mb} \\
\sigma^{corr} &\approx A^{2/3} B^{2/3} (A^{1/3}+B^{1/3})^2\ 40\,\text{mb} & &= A^{2}\ 160\,\text{mb} \\
\sigma^{back} &\approx A^{4/3} B^{4/3}\ 90\,\text{mb} & &= A^{8/3}\ 90\,\text{mb} \\
\sigma^{incl} &\approx A^{2/3} B^{2/3} (A^{1/3}+B^{1/3})\ 35\,\text{mb} & &= A^{5/3}\ 70\,\text{mb}
\end{aligned} \tag{5}$$

with the masses A and B of the colliding nuclei. As a result, already for a collision system as light as carbon on carbon the knock-out component is at the percent level of the total coincidence yield. Were it not for the strong focusing of this component into a narrow part of the two-particle phase space, it would not be noticeable at all! The height of the knock-out component (4) is given by (A-5)

$$\max_{\vec{p}\,\vec{p}\,'} F_{11}(\vec{p}\,\vec{p}\,') \approx 25/[(2\pi)^3 P_{cm}^2\, k_A k_B (k_A^2 + k_B^2)] \tag{6}$$

At a beam energy of 800 MeV per nucleon this value exceeds by almost three orders of magnitude the corresponding value of the two-particle spectrum arising in the thermal limit (at the same $\vec{p},\vec{p}'$ as above)

$$F_{11}^{therm} \approx 2 / \left[\left(\frac{2\pi e}{3}\right)^3 P_{cm}^{\,6} \right] \tag{7}$$

Above k_A, k_B denote the Fermi momenta of the two colliding nuclei, and P_{cm} is the NN c.m. momentum.

In accordance with the presently available data[1,2] we discuss the ratio R of the in to out-of plane coincidence rate of the protons

$$R(\vec{p}) = \frac{\sigma_{AB}(\vec{p}, \mathcal{D}(180^\circ))}{\sigma_{AB}(\vec{p}, \mathcal{D}(90^\circ))} \tag{8}$$

with one proton observed at lab momentum $\vec{p}$ (spectrometer) and the second one accepted in a domain in momentum space $\mathcal{D}(\varphi)$ (tag counter). Here φ specifies the azimuthal angle between the two protons (for details see ref. [1]). To simulate the experimental setup in ref. [1,2] we choose $\mathcal{D} = \left\{ E_{lab} > 200 \text{ MeV}, \theta_{lab} \in [33.^\circ75,\ 45^\circ] \right\}$.

Figure 1 shows the various contributions to the ratio $R(\vec{p})$. These are the φ-independent background $\sigma^{back}(\vec{p},\mathcal{D}) = \sigma^{back}(\vec{p},\mathcal{D}(180^\circ)) = \sigma^{back}(\vec{p},\mathcal{D}(90^\circ))$, the out-of plane correlation part $\sigma^{corr}(\vec{p},\mathcal{D}(90^\circ))$, and the in-plane correlation part $\sigma^{corr}(\vec{p},\mathcal{D}(180^\circ))$, with the knock-out contribution filling up the hatched area. Since the coincidence arrangement is aimed at isolating the elastic quasi-free NN component the respective isobar channel NN → NΔ → NNπ plays a minor role. The discussion can be simplified through the empirical observation that both the background and the out-of plane correlation part are approximately proportional to the inclusive cross section:

$$\sigma^{back}(\vec{p}, \mathcal{D}) \sim \sigma^{corr}(\vec{p}, \mathcal{D}(90°)) \sim \sigma^{incl}_{AB}(\vec{p}) \quad , \quad \mathcal{D} \text{ fixed} \tag{9}$$

Thus

$$R(\vec{p}) - 1 \sim \sigma^{corr}_{AB}(\vec{p}, \mathcal{D}(180°)) \;/\; \sigma^{back}_{AB}(\vec{p}, \mathcal{D}) \tag{10}$$

Inspection of Fig. 1 shows that the position of the quasi-elastic peak in R is strongly influenced by the $\vec{p}$-dependence of the background and also by that part of the in-plane correlation that results from clusters with more than two nucleons, cf. the discussion already given in ref. [6].

Figure 2 shows the correlation structure in the rapidity plane ($y_{\parallel} = \text{atanh}(p_{\parallel} c/E)$, $y_{\perp} = p_{\perp}/mc$) for two different angles of the tag counter. Clearly the quasi-elastic peak moves accordingly. It should be noted that while the NN cross section grows in forward direction the in-plane enhancement does not. This results from two effects, i) the background grows also towards forward angles as the inclusive cross section does and ii) in and out-of plane, of course, become more alike as one approaches the beam direction. Both effects may hinder the reconstruction of the knock-out component from the data, an information desired for a more detailed understanding of the quasi-free scattering in 'matter'.

While for nuclear collisions[1-4] the quasi-free scattering represents a negligible component of the inclusive spectra and appears only marginally visible in coincidence measurements on light systems, it becomes the dominant component in proton-induced reactions[2,12,13] because: i) there is only one participant cluster present in these reactions ($\sigma^{back} = 0$) and ii) the absence of Fermi motion in the projectile focuses the quasi-free peak at forward angles to such a degree that it grows clearly visible in inclusive (p,p') data[13]. Most of the quasi-free scattering studies by means of (e,e'), (e,e'p), (p,p') and (p,2p) reactions (e.g. ref. [13-16]) were done in a regime where the emitted nucleon(s) had a relatively moderate energy ($\gtrsim$100 MeV) so that optical re- and diffraction of the in- and out-going waves perturbed the analysis. Nevertheless, high-resolution coincidence data[16] clearly showed the structure of deeply lying s and p hole states in light nuclei. At high energies the above-mentioned perturbations play a minor role, but rescattering is dominant. While DWBA models can only account for the single scattering mechanism (knock-out), our approach includes also the rescattering contributions. Since in the presently available high-energy data[2] one of the protons is observed without energy resolution, different nuclear orbitals are not resolved and the initial intrinsic nuclear motion may be approximated by a smooth Fermi momentum distribution.

The various cross sections for 800-MeV protons on carbon are shown in Fig. 3. At forward angles (15^{o}) the inclusive proton cross section clearly exhibits the quasi-free scattering peak. However, at more sideward angles (40^o) this peak is competing with about the same amount of rescattering contributions. The simultaneous detection of another proton at $\theta_{tag} = 40^o$ makes the quasi-free scattering peak reappear in the in-plane coincidence spectrum. Our overestimation of this peak by about a factor of two may be partly due to the schematic NN cross section used but possibly also partly due to the underestimation of rescattering inherent in our straight-line assumption; cf. the mean free path discussion in ref. [2).

In conclusion, we have presented a simple multiple-collision study which complies with observed inclusive proton and two-proton coincidence data. As a result, we find the inclusive cross section of heavy-ion induced reactions (and at large lab angles also of proton induced reactions) to be dominated by multiple-scattering components. Only through the coincidental observation of two protons can the quasi-free scattering component (knock-out) be isolated. The qualitative and near-quantitative agreement of our model with the data appears to exclude models solely based on single-scattering mechanisms. A careful study of the quasi-free coincidence rate as a function of scattering angles and nuclear masses might provide information about the nuclear opacity. Yet, the possibility for studying the off-shell or in-medium behavior of the NN scattering (e.g. precritical scattering) appears still far from reach.

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Appendix (Tools)

i) Formation cross section in straight line estimate:

$$\sigma_{AB}(MN) = \int d\vec{s}\, \frac{d\vec{s}_A\, d\vec{s}_B}{\sigma_{NN}^{tot}}\ \delta(\vec{s}-\vec{s}_A-\vec{s}_B)\, P_{MA}(\vec{s}_A)\, P_{NB}(\vec{s}_B)$$

(A.1)

$$\sigma_{AB}(MNM'N') = \int d\vec{s}\, \frac{d\vec{s}_A\, d\vec{s}_B}{\sigma_{NN}^{tot}}\ \frac{d\vec{s}_A{}'\, d\vec{s}_B{}'}{\sigma_{NN}^{tot}}\ \delta(\vec{s}-\vec{s}_A+\vec{s}_B)\ \delta(\vec{s}-\vec{s}_A{}'+\vec{s}_B{}')$$

$$\times(1-\sigma_{NN}^{tot}\ \delta(\vec{s}_A-\vec{s}_A{}'))\, P_{MA}(\vec{s}_A)\, P_{NB}(\vec{s}_B)\, P_{M'A}(\vec{s}_A{}')\, P_{N'B}(\vec{s}_B{}')$$

with

$$P_{MA}(\vec{s}_A) = \frac{1}{M!}\,(\bar{N}_A(\vec{s}_A))^M\, e^{-\bar{N}_A(\vec{s}_A)}$$

$$\bar{N}_A(\vec{s}_A) = \sigma_{NN}^{tot}\int_{-\infty}^{\infty} dz_A\ \rho_A(\vec{s}_A, z_A)$$

(A.2)

ρ_A and ρ_B being the nuclear matter densities.

ii) Gaussian shape Fermi distributions

$$\omega_A(\vec{p}_F) \sim \exp\left(-\frac{p_F^2}{2\kappa_A^2}\right) \quad , \quad \kappa_A^2 = \frac{1}{5}k_A^2$$

(A.3)

with k_A being the equivalent Fermi momentum.

iii) Schematic NN (NΔ) cross section of gaussian form in four-momentum transfer

$$\frac{d\sigma}{d\Omega_{cm}} \sim e^{t/2Q^2} \quad , \; Q = 366 \text{ MeV/c} \qquad \text{(A.4)}$$

for details see ref. [8].

iv) Closed form for the elastic knock-out components

$$F_{11}^2(\vec{p}\,\vec{p}\,') = 2\left[\sigma_{NN}^{tot}\, P_{cm}^2\, (2\pi)^2\, \kappa_A \kappa_B\, (\kappa_A^2 + \kappa_B^2)\right]^{-1} \frac{d\sigma_{elas}}{d\Omega}$$

$$\times \exp\left\{ - \frac{P_{A\parallel}^2}{2\kappa_A^2} - \frac{P_{B\parallel}^2}{2\kappa_B^2} - \frac{(\vec{p}_\perp + \vec{p}\,'_\perp)^2}{2(\kappa_A^2 + \kappa_B^2)} \right\} \qquad \text{(A.5)}$$

with $P_{A\parallel}$ and $P_{B\parallel}$ satisfying energy and parallel momentum conservation

$$\frac{E_A}{m} P_{A\parallel} + \frac{E_B}{m} P_{B\parallel} = p_\parallel + p'_\parallel - P_A - P_B$$

$$\frac{P_A}{m} P_{A\parallel} + \frac{P_B}{m} P_{B\parallel} = E + E' - E_A - E_B \qquad \text{(A.6)}$$

E_A, P_A, E_B, P_B being the energy and momenta (per nucleon) of the nuclei.

References

1) S. Nagamiya et al., J. Phys. Soc. Jpn. 44, Suppl. (1980) 378; S. Nagamiya et al., Phys. Lett. 81B (1979) 147.

2) I. Tanihata et al., LBL-10694, subm. to Phys. Lett.; LBL-11488, in preparation.

3) J.W. Harris, Winter Workshop on Nuclear Dynamics, Granlibakken, California (March 1980), LBL-10688, p. 89.

4) W.G. Meyer, H.H. Gutbrot, Ch. Lukner and A. Sandoval, Phys. Rev. C22 (1980) 179.

5) J. Randrup, Nucl. Phys. A316 (1979) 509.

6) J. Knoll, Phys. Rev. C20 (1979) 773.

7) J. Cugnon, Cal Tech preprint MAP-9, (1980).

8) Y. Yariv and Z. Fraenkel, Phys. Rev. C20 (1979) 2227, and to be published.

9) J. Hüfner and J. Knoll, Nucl. Phys. A290 (1977) 460.

10) J. Randrup, Phys. Lett. 76B (1978) 547.

11) J. Knoll and J. Randrup, Nucl. Phys. A324 (1979) 445.

12) J. Cugnon, J. Knoll and J. Randrup, LBL-11301 (1980), subm. to Nucl. Phys. A.

13) G. Jacob and Th.A.J. Maris, Rev. Mod. Phys. 45 (1973) 6.

14) R. Chrien et al., Phys. Rev. C21 (1980) 1014.

15) J. Mongey et al., Phys. Rev. Lett. 41 (1978) 24.

16) J. Mongey et al., Nucl. Phys. A262 (1976) 461.

Figure Captions

Fig. 1. 800 MeV/n carbon on carbon reaction, analyzed at 90° c.m. angle as a function of transverse momentum. Upper part: invariant cross sections for proton inclusive and proton coincidence yields with a tag counter at $\theta_{lab,tag} = 40^{\circ}$. For the in-plane correlation part σ^{corr}, the hatched area represents the contribution from knock-out scattering (M = N = 1). Lower part: the in to out-of plane ratio R, hatched area from knock-out, data from ref. [1].

Fig. 2. Contour plot of R in the rapidity plane $(y, p_{\perp}/mc)$ of the spectrometer proton for two tag-counter positions. The dashed line indicates the 40° lab angle.

Fig. 3. 800 MeV proton induced reaction. As a function of lab momentum, the inclusive (invariant) cross section at 15° and 40° together with the 40° knock-out contribution split into its elastic KO and inelastic (isobar) KO(Δ) component. The in and out-of plane coincidence yields are for $\theta = \theta_{tag} = 40^{\circ}$. Data from ref. [2].

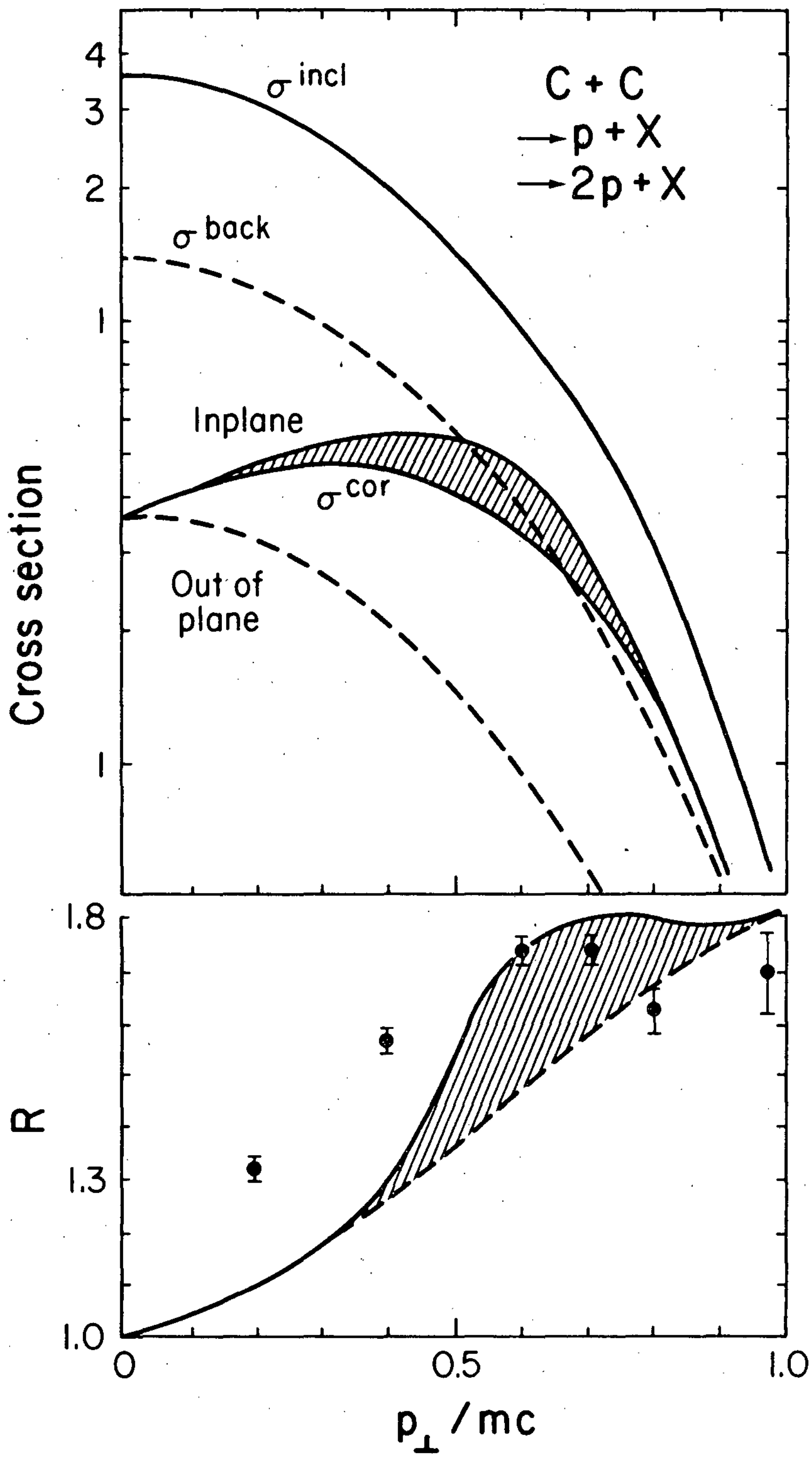

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Fig. 1

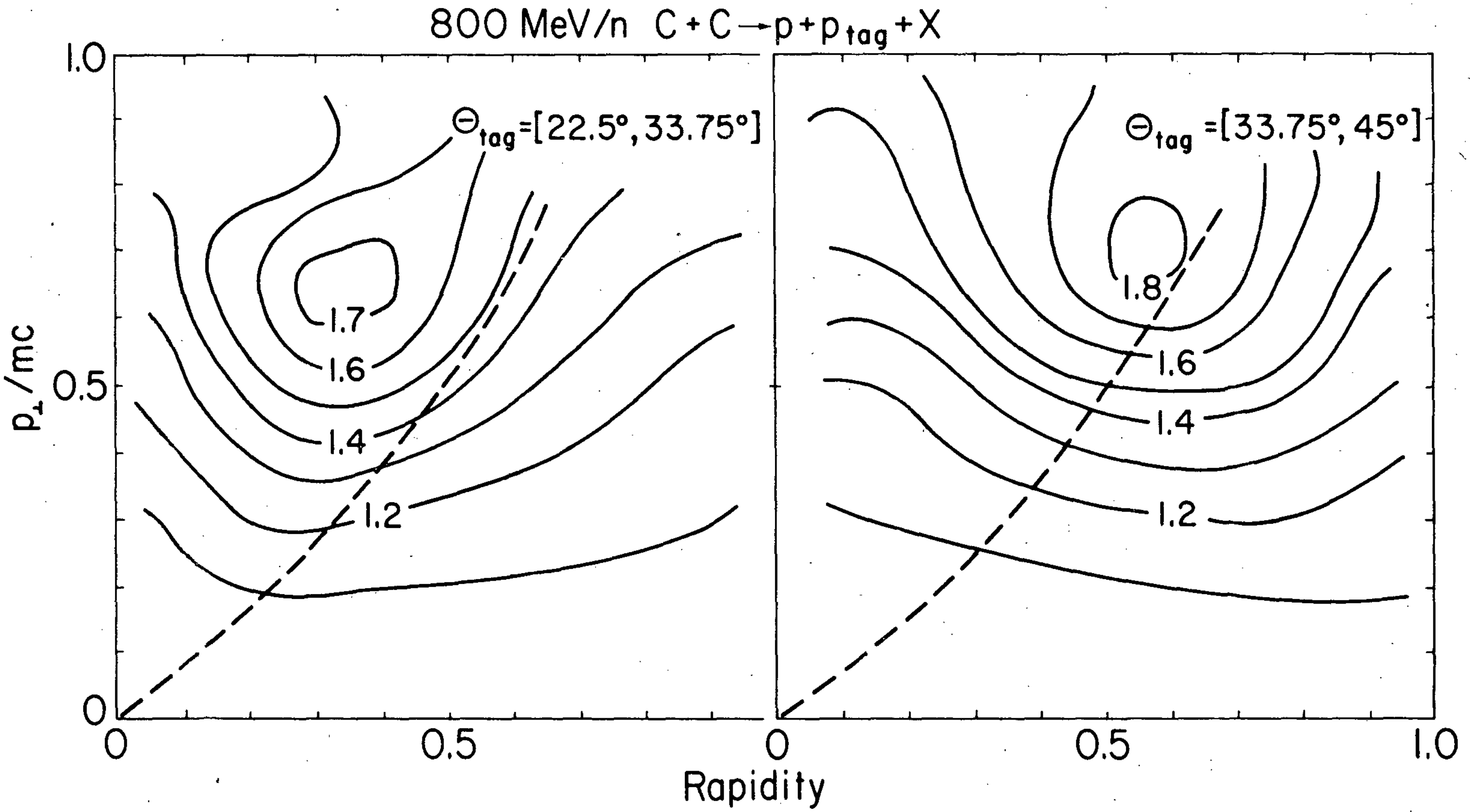

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Fig. 2

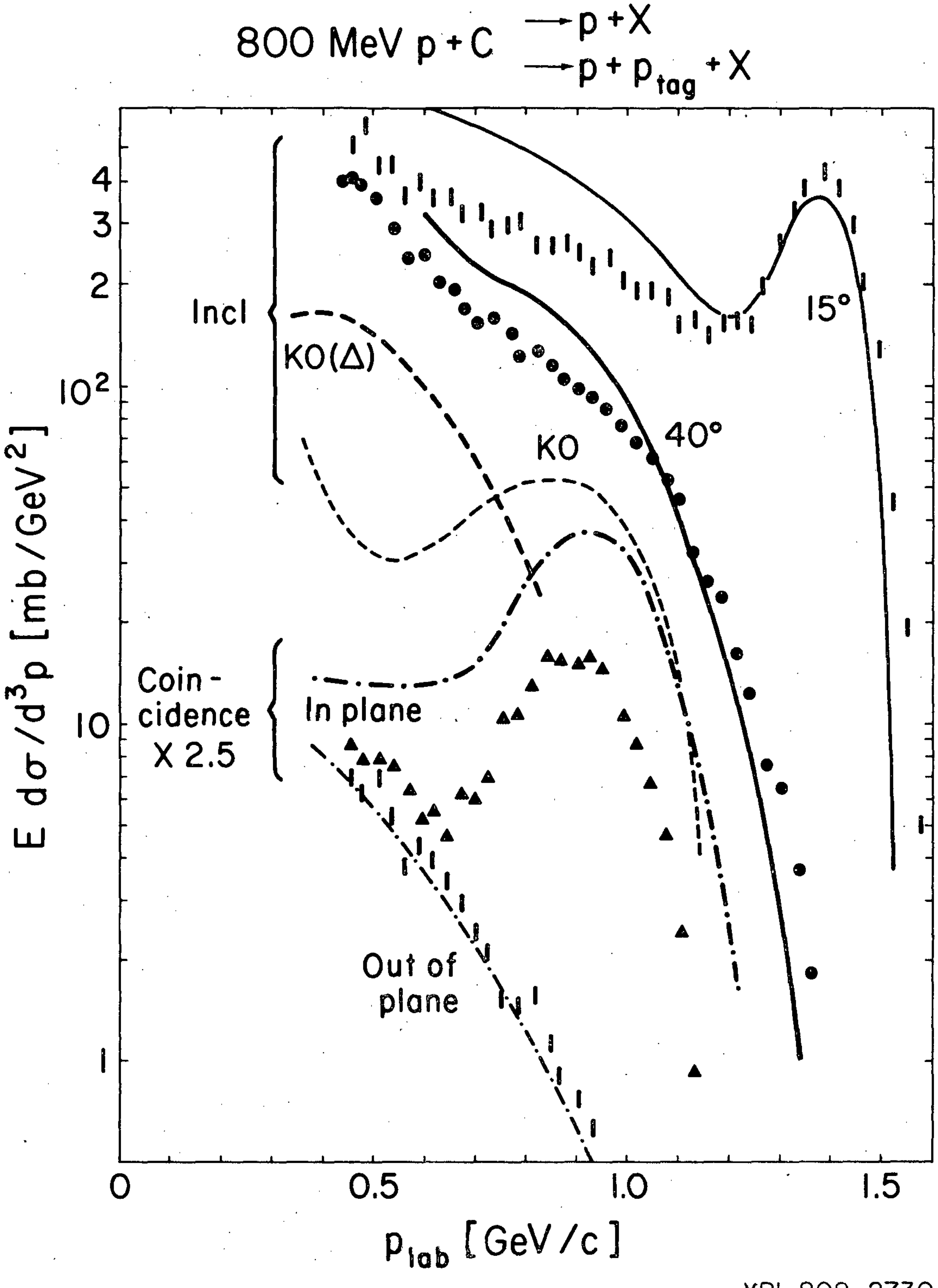

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Fig. 3

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720