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Emission Patterns in Central and Peripheral Relativistic Heavy-Ion Collisions

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Proton emission in relativistic nuclear collisions is examined for events of low and high multiplicity, corresponding to large and small impact parameters. Peripheral reactions exhibit distributions of protons in agreement with spectator-participant decay modes. Central collisions of equal-size nuclei are dominated by the formation and decay of a fireball system. Central collisions of light projectiles with heavy targets exhibit an enhancement in sideward emission which is predicted by recent hydrodynamical calculations.

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In recent analyses of single-particle inclusive data from relativistic nuclear collisions a general lack of sensitivity has been observed to the basic assumptions of various models[1-7] put forward to describe the interaction mechanism. This insensitivity results from the averaging implicit in such data over both the impact parameter and the correlation structure of the multiparticle final state.

The aim of the Letter is to present proton emission data sorted into mostly peripheral or mostly central collisions by selecting events with a low or high associated multiplicity of charged particles. There is ample indication[6] for a monotonic inverse relationship between the true mean multiplicity $\langle M\rangle$ and average impact parameter $\langle b\rangle$. Associated multiplicities well above or below the mean should preferentially select b values smaller or larger than $0.5b_{max}$. The domain of $b<0.5\times b_{max}$ corresponds to selecting events with complete diving of the light projectile into the heavy target nuclear matter. This type of high-multiplicity, violent event will henceforth be referred to as a "central" collision.

The experiments were carried out at the Bevalac accelerator with beams of p, He, Ne, and Ar at 0.25- to 2.1-GeV/u incident energy on targets ranging from Al to U. Presented here are the first results on the multiplicity-selected proton spectra ($12\leq E\leq 210$ MeV) as measured in a solid-state detector telescope. The data are selected for both high and low associated multiplicity as recorded in an array of eighty plastic scintillator detectors located with approximate azimuthal symmetry for $10°\leq\theta_{lab}\leq 80°$. The array is sensitive to charged particles above a lower energy cutoff corresponding to 15 MeV for pions and 25 MeV for protons. The details of the experimental arrangement have been described elsewhere.[8]

The detector telescope was movable from $\theta_{lab}=10°$ to $150°$ inside the vacuum chamber. For angles forward of 80° a certain number of the multiplicity array detectors were in the geometrical shadow of the telescope material. In order to remove possible effects of particle absorption or secondary interactions on the measured multiplicity distributions, all shadowed detectors were excluded from the analysis. The number of these counters is small and their removal does not affect the results. Furthermore, the beam intensity was maintained at a level such that the accidental contribution to the mean value $\langle m \rangle$ of the observed distribution was well below 1 at all angles. The response of the array was found to be independent of the telescope position and beam intensity by use of a fixed, separate, monitor detector telescope that recorded ^{4}He fragments of about 80-MeV energy.

Low- and high-multiplicity selections (cuts) were applied to the single-particle inclusive data thus defining peripheral and central events. The procedure chosen was to consider, in each reaction studied, the observed multiplicity distribution associated with protons measured in the telescope at 90°. The cuts were chosen well above and below the mean of this distribution, each cut corresponding to roughly 15% of the 90° inclusive proton cross section. These cuts were then used at all other angles. The true associated charged-particle multiplicity, M, corresponding to the two cuts in measured multiplicity, cannot be determined accurately.[8] Our definition of central or peripheral reactions does not, therefore, correspond to a sharp cutoff in M or b. However, it is well defined and should be directly applicable to theoretical calculations.

The overall effect of high versus low multiplicity selection on the proton emission pattern is illustrated in Fig. 1 showing contour diagrams of the invariant cross section in the plane of transverse momentum and rapidity. The contour lines are constructed by a smooth interpolation of multiplicity selected spectra obtained at 30° (20° for some cases) to 150° in steps of 20°. They are superimposed for high and low multiplicity selections.

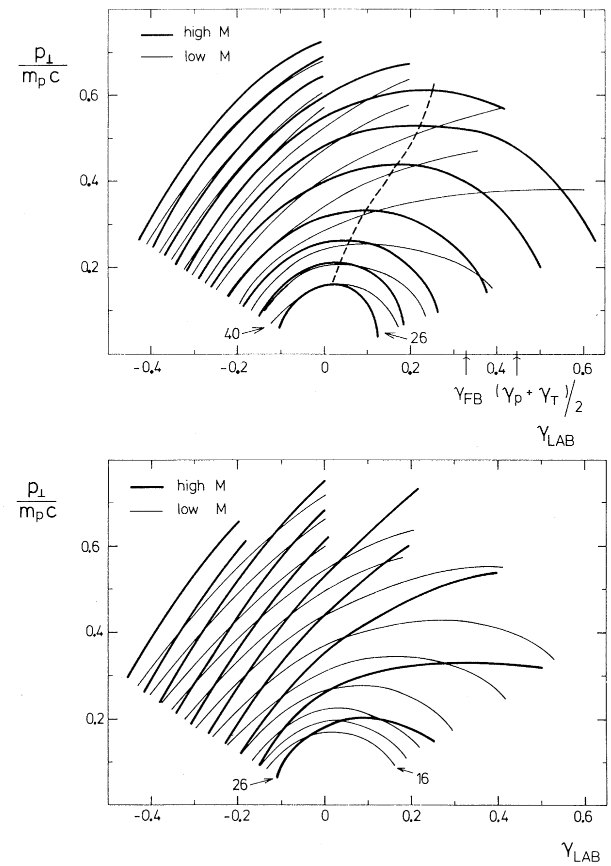

FIG. 1. Contour diagrams of invariant proton cross section for peripheral (thin lines) and central (thick lines) collisions, in the plane of transverse momentum (in units of $p_\perp / m_p c$) and rapidity $y = \frac{1}{2} \ln [(E + p_\parallel)/(E - p_\parallel)]$. Five lines are drawn for each decade of invariant cross section. Absolute cross-section scales are indicated for each set of lines, in units of μb/sr MeV^2 c^{-1}. The cases illustrated are ^{20}Ne + U at 393 MeV/A (top) and ^{40}Ar + ^{40}Ca at 1.04 GeV/A (bottom).

The typical cases chosen here to illustrate the effects found in the data are ^{20}Ne + U at 393 MeV/u and ^{40}Ar + Ca at 1.04 GeV/u. The most important observations from a comparison of these patterns are as follows:

(i) For the heavy-target cases (^{20}Ne and ^{40}Ar on Ag to U) central collisions exhibit a universal trend of the contour lines centering approximately near zero (target) rapidity. The shape of the contour line is roughly semicircular about rapidities ranging from 0 to about 0.2, in the case illustrated here, indicating a continuous shift in apparent longitudinal source velocities as shown by the dashed line. This implies that there is no unique source for proton emission. The source velocities thus range from 0 to 0.25c for the bulk of the proton cross section which is observed up to transverse momenta of about 600 MeV/c. This cross section thus appears neither at fireball rapidities, which are at $y = 0.33$ for impact parameters smaller than $0.5b_{max}$ in this case, nor at the corresponding nucleon-nucleon center-of-mass rapidity $\frac{1}{2}(y_p + y_t) = 0.45$.

(ii) The peripheral-collision contour lines are primarily determined by the incident energy. Their shapes are almost insensitive to the choice of target and projectile, with source velocities rapidly shifing from the target domain to the mid-rapidity domain for increasing $p_\perp$. The products of single binary nucleon collisions, with superimposed Fermi motion, are discernible in phase space.

(iii) Unlike the heavy-target cases, the central collisions of equal-size nuclei, such as $^{40}Ar + Ca$ and $^{20}Ne + ^{27}Al$, exhibit contour lines dominated by the decay of a mid-rapidity source for the bulk of the observed cross section. Note that the contours for high multiplicity in $^{40}Ar + Ca$ shift towards high rapidities $[\frac{1}{2}(y_p + y_t) = 0.67$ in this case$]$ even faster than the corresponding low-multiplicity contours, contrary to the trend exhibited by Ne + U.

The peripheral-collision data thus appear qualitatively consistent with models including direct knockout plus spectator decay.[1,9] Central collisions of nearly equal-mass nuclei, such as Ar + Ca and Ne + Al, seem to create a composite system moving with the fireball rapidity. On heavy nuclei, however, central collisions seem to form a highly excited system that is moving relatively slowly in the laboratory frame. This effect indicates a transverse spreading of the incident energy across the heavy target nucleus, to a degree much higher than is implied by the geometrical localization assumed in the fireball model. The projectile does not sweep out a fireball but appears rather to be stopped inside the target matter.

The nature of the energy flux into the target nuclear matter may be analyzed in more detail by considering the proton angular distributions givin Fig. 2. They are represented in the laboratory frame, for various momenta ranging from 150 to 625 MeV/c, corresponding to proton energies from 12 to about 200 MeV. The high-multiplicity selected differential cross sections are shown for the cases $^{20}Ne + U$ at 0.393 and 2.1 GeV/u, as well as $^{40}Ar + U$ and $^{40}Ar + Ca$ at 1.04 GeV/u. The low-multiplicity selection data for Ne + U are shown for comparison, and finally the high-multiplicity proton yield for $p + U$ at 1.04 GeV. The latter reaction exhibits almost isotropic angular distributions at low proton energies, and slightly forward peaked preequilibrium emission towards the higher energies. A suppression of forward emission or even a sideward peaking is observed in the central Ne and Ar collisions on heavy targets. The peak positions exhibit a systematic shift from about 30° at 625 MeV/c to about 90° at the lowest momenta. With increasing incident energy there is a slight trend towards larger angles in the peak positions of each momentum bin. This trend is absent in the peripheral $^{20}Ne + U$ data, as well as in central $^{40}Ar + Ca$ reactions. In collisions of light projectiles with heavy targets, deuteron emission (not illustrated here) shows

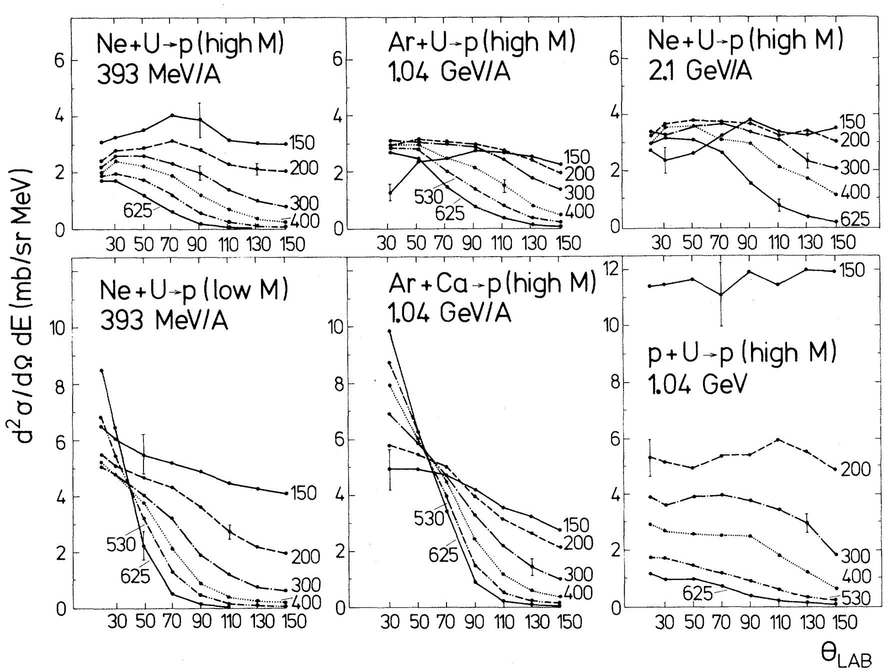

FIG. 2. Angular distributions of protons at different laboratory momenta ranging from 150 to 625 MeV/c, from reactions selected for high and low multiplicity. Cross sections are represented by data points and straight connecting lines to guide the eye. Typical error bars are given that include statistics and interpolation uncertainties.

structure similar to the proton data, but with the peaks in $d^2\sigma/d\Omega\,dE$ shifted forward in angle when the same momentum per nucleon is considered.

Observations related to ours have recently been made by Nagamiya *et al.*[10] where an associated multiplicity selection was applied to proton spectra ($100 \leq E \leq 2000$ MeV) from the reaction of 800-MeV/u ^{40}Ar + Pb. Previously, Schopper *et al.*[11] reported a sideward peaking in the angular distributions, $d\sigma/d\theta$, for $Z = 1, 2$ fragments emitted in central (high multiplicity) collisions of ^{4}He and ^{12}C projectiles with Ag nuclei. Previous searches in inclusive experiments did not reveal any such features.[4,12]

A challenging aspect of the present data, in addition to the general suppression of forward emission in central, heavy-target collisions, is the systematic shift of the observed sideward yield with the proton energy. Although this rules out a simple "Mach peak"[2] the data might be understood in terms of a realistic hydrodynamical model as a collective and dispersive sideward flow of matter initiated early in the collision, during penetration.[2,3,13] This would also explain why we do not observe the same phenomenon in collisions of nuclei with similar mass. This effect indicates that the origin of the observed phenomena is not of a simple kinematic nature. Recent cascade calculations by Yariv and Fraenkel[6] have addressed this effect specifically, both for the data of Ref. 10 as well as for the data on ^{20}Ne + U at 393 MeV/u presented here. These calculations do not reproduce the sideward peaking. Hydrodynamical calculations,[14] however, lead to an overall agreement with the present data.

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