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Mass-Independent Correlation of Fragment Velocity and Source Velocity in Nucleus-Nucleus and Proton-Nucleus Collisions

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Abstract

For multi-GeV/nucleon bombarding energies and for emission velocities $\lesssim 0.4$ c, all fragments of nucleus-nucleus and proton-nucleus collisions are emitted isotropically in a recoiling source frame. For a given reaction the radial emission velocity in the source frame has about the same strong positive correlation with source velocity, independent of mass. Such behavior is uncharacteristic of a thermalized source.

In this Letter we point out some important common features of the fragment spectra for relativistic nucleus-nucleus and proton-nucleus reactions, and we indicate the difficulties these features pose for thermal models.[1-4]

We have analyzed published data for the following reactions: 400 MeV/N Ne + U → X + anything, with X = ^{1}H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, Li, ^{7}Be, ^{9,10}Be, B, C, and N (refs. 5-7); 500 MeV/N Ar + Au → X + anything, with X = ^{8}Li, Be, B, C, N, O, F, Ne, and Na (refs. 6,8); 2.1 GeV/N Ne + U → X + anything, with X = ^{1}H, ^{3}H, ^{3}He, ^{4}He, Li, ^{7}Be, ^{9,10}Be, B, C, and N (ref. 7); and 5.5 GeV p + U → X + anything, with X = ^{4}He, ^{7}Li, B, C, Si, and Ar (ref. 9).

Although we reach the same conclusions by a numerical analysis, it is easier to visualize the fragment emission patterns if we plot contours of constant invariant cross section in momentum space. We first convert data in the form of $d^2\sigma/dEd\Omega$ as a function of kinetic energy into invariant cross section, $\sigma_{inv} = P^{-1}d^2\sigma/dEd\Omega$, as a function of momentum, P, for the various lab angles studied. After fitting smooth curves through these data, we then construct contours of constant σ_{inv} in momentum space, as shown in Fig. 1. For all of the data we analyzed, the velocities of the fragments and "source" frames are low enough that a Galilean transformation is valid. Thus, isotropic emission from some moving source would lead to a circular contour centered on the source momentum and with radius equal to the momentum of the fragment in the source frame. Dividing by the fragment mass, we then find the source velocity, β_s, and the radial velocity, β_r, of the fragment in the source frame, valid for a particular value of the invariant cross section. Several examples of the graphical construction are shown in Fig. 1. The labels on the contours give the logarithm of σ_{inv} in units $\mu b/sr(MeV)^2/c$.

Perhaps the most remarkable feature of the graphs is the extremely isotropic emission of all fragments, in the appropriate moving frame, for the reactions at multi-GeV/N energies. The best fits to the contours of constant σ_{inv} for the reactions 5.5 GeV p + U → C and 2.1 GeV/N Ne + U → ^{7}Be, shown in Fig. 1, are circles with centers on the positive $P_{\|}$ axis. The centers of the circles move to increasing values of $P_{\|}$ as the radii of the circles increase. For all other fragments from the 2.1 GeV/N Ne + U and 5.5 GeV p + U reactions the contours are also accurately circular. For the 400 MeV/N Ne + U fragment data the contours are approximately circular at angles larger than ~60°, but there is an additional contribution to σ_{inv} at angles near the forward direction, as can be seen in Fig. 1(c). When we fit the data at large angles to circles, we find that their centers move along the positive $P_{\|}$ axis to values that increase with their radii. Data for the reaction 500 MeV/N Ar + Au are available only at angles from ~35° to ~80°. These data are consistent with isotropic emission within this interval, but we cannot rule out an additional contribution to σ_{inv} at larger or smaller angles.

The locations of the centers of the circles for all data we have analyzed correspond to source velocities $\beta_s < 0.2$; in the majority of cases $\beta_s < 0.1$. In terms of the relativistically invariant rapidity, the source rapidity, $y \equiv \tanh^{-1} \beta$, is much closer to the target rapidity, $y = 0$, than to the beam rapidity. The rapidity gap between the target fragmentation region and the projectile fragmentation region is much greater for the 2.1 GeV/N Ne + U reactions and the 5.5 GeV p + U reactions than for the 400 MeV/N Ne + U and 500 MeV/N Ar + Au reactions. It is thus not surprising that isotropic emission from a system closely associated with the target should be more clearly separated from contributions from the projectile and from sources of intermediate rapidity (a fireball?) for the multi-GeV/N reactions than for reactions at lower energy.

Figure 2 shows the correlations between β_s and β_r that we find from graphical analyses of the four reactions. For the 400 MeV/N Ne + U data we chose β_s and β_r for circular contours fitted at angles larger than or equal to 60° and ignored the anisotropy at small angles. For each reaction β_s is strongly correlated with β_r and there is no systematic shift of the correlation line with fragment mass. For fragments with a given radial velocity, β_s is about the same in the 400 MeV/N Ne + U and 500 MeV/N Ar + Au reactions, lower in the 2.1 GeV/N Ne + U reactions, and still lower in the 5.5 GeV p + U reactions. This result seems consistent with the expected[10] increase in longitudinal momentum transport length with increasing beam kinetic energy/nucleon. For each reaction the scatter of the lines for different fragments about a single correlation line appears to us to be consistent with systematic experimental errors and with possible errors in reading data from published graphs.

In their studies of fragments from proton-nucleus reactions Crespo et al.[11] and Poskanzer et al.[9] first noted the correlation of β_s and β_r and pointed out that a hot, recoiling, evaporating source does not fit the shapes of the energy spectra well. With the simplifying assumption of a single source velocity and temperature, Poskanzer et al.[9] and recently Westfall et al.[12] concluded that for proton-uranium collisions the choice $\beta_s = 0.006$ best reproduced the change in the peak value, at low energy, of the cross section $d^2\sigma/dEd\Omega$, from the lab angle of 20° to 160°. With increasing fragment energy, however, the decrease in cross section with increasing lab angle is larger than can be accounted for with the value of β_s optimized at low energy. The results of our analysis, seen in Fig. 2, show that neither a single value of β_s, nor two discrete values, as recently proposed,[12] are compatible with the data.

We interpret the mass-independent correlation of β_s with β_r as follows. Collisions at various impact parameters produce excited, recoiling sources with a wide distribution of recoil velocities and masses possibly extending up to the target mass. For each fragment the invariant cross section has its own dependence on β_s and β_r, not shown in Fig. 2. (The remarkable exponential dependence of σ_{inv} on $Am_p\beta_r$, independent of fragment mass, was discussed in ref. 13.) In the "target fragmentation" regime, collisions leading to sources with a given β_s result in isotropic emission of fragments with the same β_r. The mechanism of fragment emission, in the regime $\beta_s \lesssim 0.2$, $0.1 \lesssim \beta_r \lesssim 0.4$, involves a characteristic radial velocity instead of a characteristic kinetic energy and is thus not primarily thermal in nature.

We have used the same graphical method to analyze the mass dependence of the correlation, β_s vs β_r, calculated from several models of nucleus-nucleus collisions. The fireball model with no transparency and sharp nuclear surfaces leads to far too weak a dependence of β_s on β_r and values of β_s far above the values in Fig. 2. For the 400 MeV/N Ne + U, 500 MeV/N Ar + Au, and 2.1 GeV/N reactions the values of β_s at the impact parameter with maximum weight would be 0.27, 0.38, and 0.56 (ref. 1). Allowing the entire target to recoil (ref. 1) leads to a low, constant value of β_s and thus does not give a correlation of β_s with β_r. The introduction of transparency, using the longitudinal momentum transport length of Sobel et al.,[10] gives much too weak a dependence of β_s on β_r. For these thermal models, fragments with different mass would have correlation lines displaced such that, at fixed β_s, β_r would decrease as $A^{-\frac{1}{2}}$. W.D. Myers[3] has extended the fireball model to include a diffuse surface and to take into account the variation of the velocity and temperature across the fireball. This "firestreak" model fits experimental data better than does the fireball.[4] We find that, although it reproduces the β_s vs β_r correlation better than does the fireball, the contours of σ_{inv} calculated from the firestreak model are strongly forward peaked, even for the 2.1 GeV/N Ne + U reaction, in conflict with the isotropic contours derived from the data.

From our graphical analyses we conclude that target fragmentation appears to be a nonthermal process characterized by isotropic emission of fragments at radial velocities independent of fragment mass.

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Figure Captions

Figure 1. Contours of constant invariant cross section, σ_{inv}, in momentum space. Curves are arcs of circles except in (c) at angles less than 60° and large momenta. Labels are values of $\log_{10} \sigma_{inv}$, where σ_{inv} is in $\mu b/sr(MeV^2/c)$. Open circles in (c) are from data in ref. 7; solid points in (a), (b), and (c) are from data in refs. 10, 8, and 8 respectively.

Figure 2. Mass-independent correlations of β_s with β_r for various fragments and reactions. The dashed lines are least squares lines.

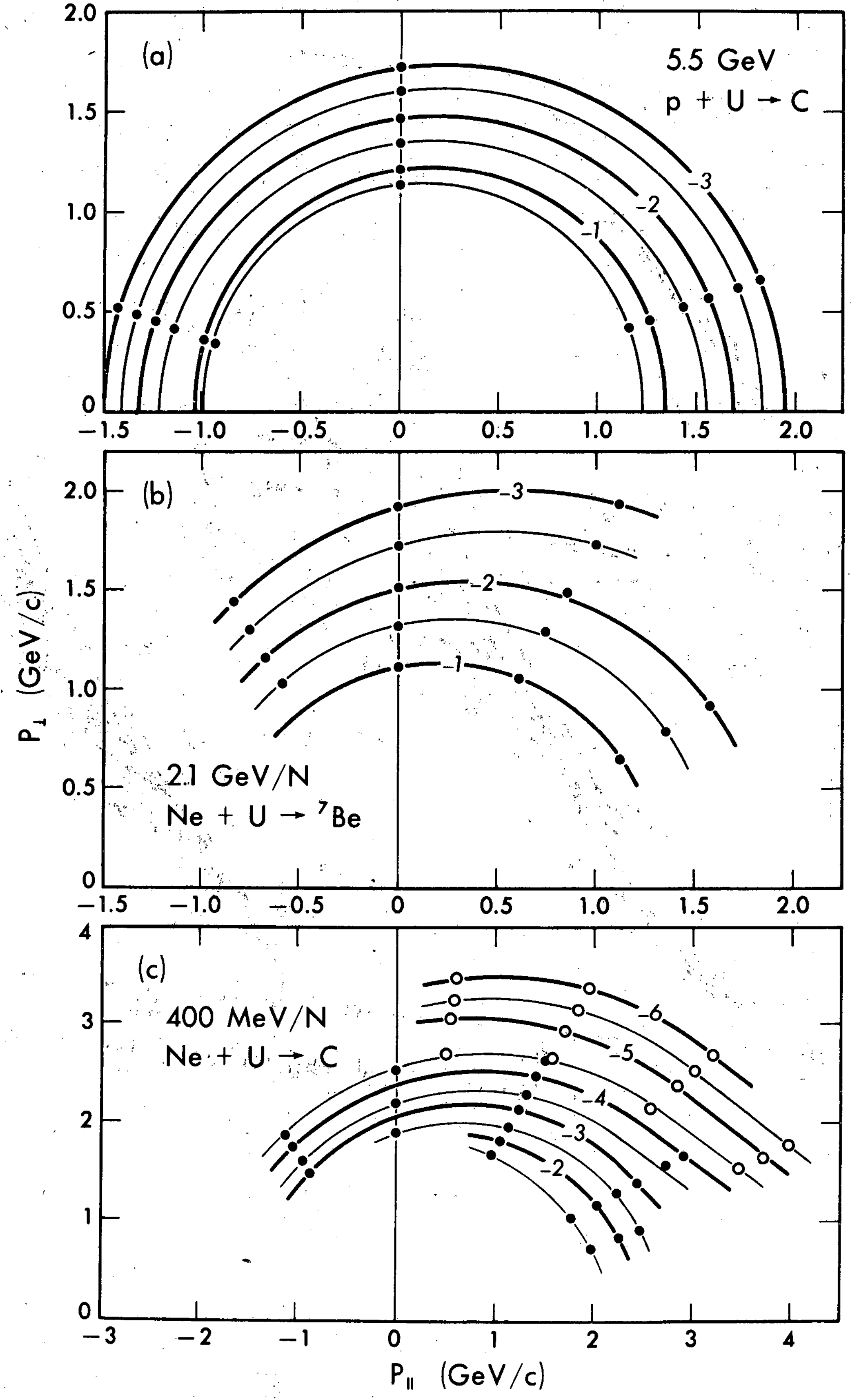
(a)
5.5 GeV
p + U → C
–1
–2
–3
(b)
–1
–2
–3
2.1 GeV/N
Ne + U → ^{7}Be
(c)
400 MeV/N
Ne + U → C
–2
–3
–4
–5
–6
P$_\perp$ (GeV/c)
P$_\parallel$ (GeV/c)
2.0
1.5
1.0
0.5
0
4
3
2
1
–1.5
–1.0
–0.5
0.5
1.0
1.5
2.0
–3
–2
–1
0
1
2
3
4

FIG. 1

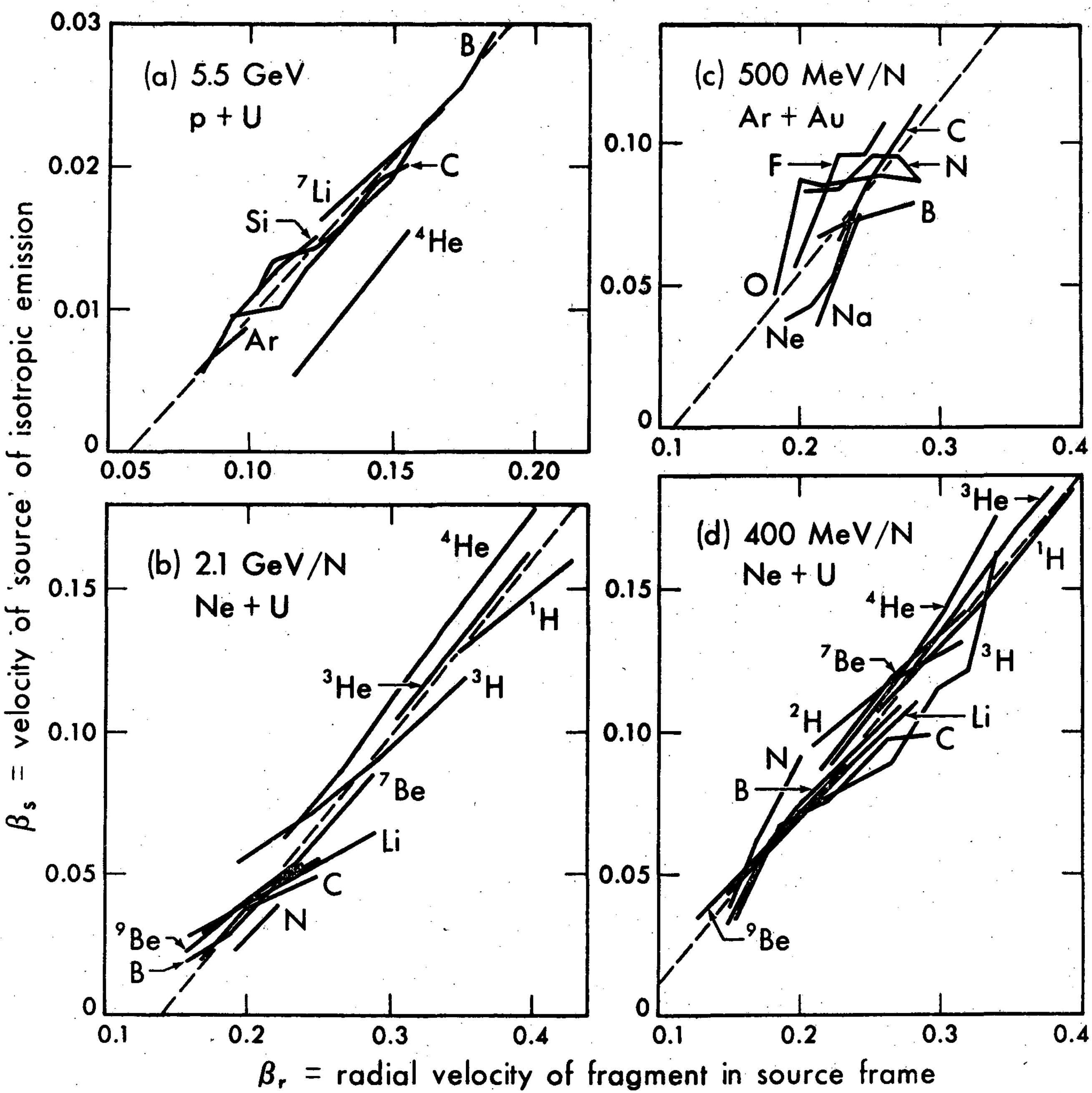
(a) 5.5 GeV
p + U
B
C
7Li
Si
4He
Ar
0.03
0.02
0.01
0
0.05
0.10
0.15
0.20
(c) 500 MeV/N
Ar + Au
C
F
N
B
O
Na
Ne
0.10
0.05
0
0.1
0.2
0.3
0.4
(b) 2.1 GeV/N
Ne + U
4He
1H
3He
3H
7Be
Li
C
N
9Be
B
0.15
0.10
0.05
0
0.1
0.2
0.3
0.4
(d) 400 MeV/N
Ne + U
3He
1H
4He
7Be
3H
2H
Li
C
N
B
9Be
0.15
0.10
0.05
0
0.1
0.2
0.3
0.4
β_s = velocity of 'source' of isotropic emission
β_r = radial velocity of fragment in source frame

FIG. 2