Forward Protons and Nuclear Transparency in Relativistic Heavy-Ion Interactions

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The relativistic cascade code ARC is applied to data from the experiment E814 covering projectile rapidities in Si+Pb collisions at 14.6 GeV/c per nucleon. The result is a quantitative theoretical description of the entire range of the experimental rapidity spectrum, as well as of the number and transverse energy dependence of "punchthrough" protons. This plus additional detailed comparisons of transverse mass distributions strongly suggest the cascade approach can be highly useful for understanding energetic ion collisions.

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A relativistic cascade (ARC) developed for treating heavy-ion interactions over a broad range of energies has given an account [1] of experimental results from target to midrapidities for nucleus-nucleus and nucleon-nucleus collisions [Refs. 2–4] at 14.6 GeV/c. The principal data confronted were from the Brookhaven Alternating Gradient Synchrotron (AGS) experiment E802 [2], covering rapidities $0.7 \lesssim y_L \leq 2.0$, by no means the full range of interest. It is important to demonstrate that the cascade works equally well for the complementary "projectile" rapidities, $y_L \gtrsim 2.0$, as observed in the experiment E814 [3,4]. If the physics of ARC gives a single coherent picture of the entire ion-ion reaction, one could then have some confidence in extrapolating this hadronic background to CERN and perhaps to Brookhaven's Relativistic Heavy Ion Collider energies. A successful theoretical synthesis of E802 and E814 would also lay to rest suggestions that E802 is not consistent with energy conservation [5,6]. It is of course essential in comparing these disparate experiments with each other or with simulations [7] to understand and impose the full regalia of experimental constraints. This is especially true of the highly selective examination of forward nucleons by E814. Our main concerns here are with the issue of nuclear stopping, or equivalently nuclear transparency, first as defined by the complete range of observed rapidities $y_L = 0.7$ to 3.8 and then more narrowly by the restricted E814 geometry and centrality for $y_L \gtrsim 3.0$. We add brief comments on the related issue of color transparency, deuteron production, and on the extent to which E814 results yield information about the nuclear surface in momentum space.

The theoretical instrument used in this analysis, ARC, was introduced in Ref. [1] and will be discussed in detail in a future extended work. The cascade was applied using two differing modes: one, labeled direct (DIR), which handled intranuclear inelastic nucleon-nucleon interactions as if they occurred in free space, and the other labeled resonant (RES), which introduced as intermediate states low-lying baryon and meson resonances. In both approaches the directly produced mesons are assigned finite formation times and more importantly the free space hadron-hadron data are *equally* well fitted. However, it is the resonant mode [1] that yields a quantitative description of E802, with DIR producing too many struck protons, too many π mesons, two few K^+'s, and more stopping. The operative distinction between RES and DIR are the higher baryon-baryon collision energies and the fewer number of π mesons produced in RES. It is even possible that an extreme version of RES, with the final state for nucleon-nucleon consisting of just two resonances of varying mass and width, will describe soft nucleon-nucleon collisions to much higher energies than considered here.

Higher mass resonances, more massive than the Δ, N^*, for example, are not much excited at the AGS [8]. Specifically at both 5.5 and 15 GeV/c laboratory momenta the excitation cross section for the $\Delta(1236)$ is at least 20 mb; for the combined $N^*(1400)$ and $N^*(1525)$ it is 5 mb. These add up to some 25 to 26 mb out of a total inelastic cross section of 28 or 29 mb. The sensitivity to higher mass resonances can be tested by using a generic resonance with a mass weighted by the actual presence in the nucleon-nucleon data. This does not alter the results discernibly, showing that it is not the mass but the momentum of the reinteracting resonances that matters. The *key dynamic point* again is the reinteraction of baryons at higher momenta, with

$$\langle k \rangle_{\rm res}^{\rm av} \sim \langle k \rangle_N^{\rm av} + \langle k \rangle_\pi^{\rm av} .$$

Interaction between resonances is of course poorly known, and here we have made the minimal assumption that BB is much like NN and MB like πN, etc.

We turn to the general question of nuclear stopping. It is a given that energy appearing in target nucleons in, say, Si+Pb, Si+Cu comes from energy lost from projectile particles. One can at any rapidity represent the nucleon spectra as a sum over contributions from nucleons which were initially present in either the projectile or the target. Thus,

$$\frac{dN}{dy} = \left(\frac{dN}{dy}\right)_{\rm proj} + \left(\frac{dN}{dy}\right)_{\rm target} .$$

At low rapidity, certainly at $y_L \lesssim 0.7$ for AGS energies,

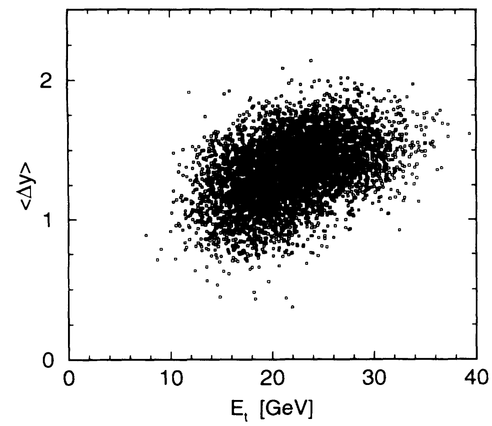

FIG. 1. Scatter plot of average rapidity loss of projectile protons per event plotted vs the transverse energy E_t of the event. E_t, calculated in the geometrical region $-0.5 < \eta < 0.8$ which corresponds to the acceptance of the target calorimeter in E814 [3], has not been corrected for experimental detector leakage [3]. A sampling of 24000 Si+Pb events with $b \leq 5$ fm provided the basis for the theoretical points shown in this and subsequent figures.

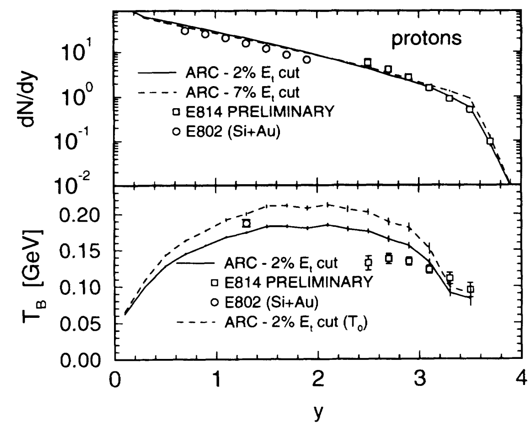

FIG. 2. Proton rapidity distribution and inverse slope parameters for Boltzmann (T_B) and exponential (T_0) transverse mass distributions. The rapidity distribution (top panel) is shown for ARC (Si+Pb, 2% and 7% E_t cut), E814 preliminary data [4], and E802 (Si+Au) [2]. The 2% E_t cut corresponds to a 70-mb cross section for E814 centrality, while the 7% E_t cut corresponds roughly to the centrality of the E802 TMA trigger. We find no difference between Si+Pb and Si+Au within the E802 rapidity window, at least with respect to geometric cuts. The m_t distributions at $y = 3.3$ and 3.5 cannot be characterized by a single slope, and therefore T_B or T_0 depends on the low m_t cutoff one uses. The theoretical T_B were calculated using a low m_t cutoff of 0.05 GeV. Detailed comparisons (Fig. 4) to the m_t distributions in the E814 rapidity range are even better than these extracted inverse slopes indicate. The E802 results shown here are not the final data [6].

the target component dominates while for $y_L \gtrsim 2.5$ only projectile nucleons are present. This decomposition is a powerful tool for understanding many features of the dynamics, for example, the evolution of the interesting baryon transverse mass, m_t, distribution from p+Au to Si+Au and finally to Au+Au. To quantify the energy loss from the projectile, we can arbitrarily integrate the nucleon rapidity spectrum down to the point where $A_{\rm proj}$ is obtained. In RES for Si+Au at 14.6 GeV/c one finds ten protons above midrapidity, $y_L \gtrsim 1.72$, and thus four nucleons are slowed to rapidities within the nominal target region. It is then possible to understand the broadening of the proton m_t in spectrum [1,2], with the effective proton "temperature" rising from low y, peaking somewhat above midrapidity, and then dropping towards higher rapidities (see Fig. 2). The maximum occurs roughly where projectile nucleons strongly influence the target rapidity region. Figure 1 is a plot of the average shift in rapidity for projectile protons in Si+Pb collisions. The overall Δy for impact parameters $b \leq 3$ fm is $\Delta y(\text{RES}) = 1.48$, corresponding to an energy loss $\Delta e_L(\text{RES}) = 11.2$ GeV. The corresponding values for DIR are $\Delta y(\text{DIR}) = 1.63$ and $\Delta e_L(\text{DIR}) = 11.7$. The greater stopping evident in DIR is even more marked for $b \leq 2$ fm, i.e., for a more central collision, and one can expect this difference to be magnified in the Au+Au collisions anticipated at the AGS. The extra transparency evidenced with RES is not sufficient, however, to preserve a distinctive projectile peak, as some authors have suggested [5] (see Fig. 2).

We reemphasize that in specific comparison with E814, it is crucial to incorporate the precise experimental cuts in centrality, geometry, and rapidity. Centrality is defined by a level of integrated cross section as a function of "transverse energy" (see Fig. 3),

$$E_t = \sum_i \epsilon_i \sin\theta_i \,.$$

One cannot accept simple theoretical equivalents such as a geometrical restriction on impact parameter b, nor can one compare two sets of experimental data with different definitions of centrality [4]. Fluctuations in E_t as a function of b are simply too large. Figures 2 and 3 display the most significant comparisons between ARC and E814 [3]. Figure 2 contains the forward rapidity spectra for a centrality defined by a 2% cut on the integrated E_t cross section [3,4] as well as target rapidity spectra from E802 (Si+Au) for a 7% cut [2]. Figure 3 shows the proton number $\langle m_p \rangle$ impinging on the narrow, rectangular E814 detector as a function of E_t for $y_L \gtrsim 3.0$. The agreement with experiment is remarkable [6], and one concludes that RES gives a truly quantitative description of both target and projectile baryons. In forthcoming work we will exploit this success to predict results for Au+Au, including the levels of energy and baryon densities achieved in such collisions. In contrast, DIR yields about half the value of $\langle m_p \rangle$ seen in RES; thus, the experiment seems to distinguish between these two models.

These results also rule out any necessity for color transparency [9], in which large fluctuations in nucleon size associated with valence quarks occupying, for example, a much smaller spatial volume lead to increased penetration through the target. There indeed is an enhanced nuclear transparency in RES, but this is attributable to the higher projectile baryon transit energies and to reduction in produced mesons at all rapidities. These cascade effects mask any possible small contribution from color transparency at these and probably even at higher energies. It is unlikely that a purely Glauber calculation can be trusted here, ignoring as it does rescattering off produced secondaries as well as the presence of baryon resonances.

It is possible to subdivide the forward protons in Fig. 3 into three categories: (I) noninteracting projectile nucleons, (II) and (III) elastically and inelastically interacting nucleons. These categories may be distinguished, in principle, by their transverse mass spectra with (I) possessing the narrowest distribution ($T_{\rm eff}^{\rm I}=0.04$ GeV) characterized by the projectile Fermi momentum and (II) and (III) successively broader ($T_{\rm eff}^{\rm II}\approx 0.07$, $T_{\rm eff}^{\rm III}\simeq 0.07$–$0.15$) distributions. In the ARC RES simulation, the events seen are roughly divided equally between only two categories, i.e., between (I) and (II,III). In Fig. 4 are displayed simulated and experimental [3,4] m_t distributions for the most forward rapidity bins and it is clear that the two components are present. With the sharp Fermi sea used in the calculation one naively expects no protons with $y_L \gtrsim 3.53$ and those seen for $3.6 \le y_L < 3.8$ must be knock-on baryons struck from behind by high rapidity mesons. The apparent agreement between RES and E814 in levels of both "narrow" and "broad" protons argues against appreciable tails above the Fermi surface. We note the use by E814 of "Boltzmann" thermal distributions [4] with

$$\frac{d^2N}{dm_t^2\,dy} \sim m_t \exp(-m_t/T_B)$$

as distinct from

$$\frac{d^2N}{dm_t^2\,dy} \sim \exp(-m_t/T_0)$$

used elsewhere [1,2]; T_B (Fig. 2) is generally 15% lower than T_0. In any case, we emphasize again that our results vitiate strongly against thermalization of these most forward protons and the use of effective temperatures is only figurative.

An interesting aspect of the E814 forward nucleon measurements is an observed strong pp correlation [3,4]. From Fig. 3 one could extract the probability of emitting a single forward proton, detected in E814, as approximately 0.7%. However, both experiment and the cascade suggest a much larger, approximately 5%, likelihood of detecting a second proton in the same geometrically limited event. This correlation results theoretically from the tendency for any "punchthrough" nucleons to be at relatively high impact parameter and thus there is an enhanced probability of a second proton in the projectile transiting the same "hole" in the target. Even higher levels of correlation, $\sim 2\times 5\%$, exist in the simulation for np pairs and given the effective binding in the projectile, one can expect a surprisingly high flux of preformed forward deuterons.

The results presented here for projectile nucleons must of course be seen in the context of the entire ion-ion col-

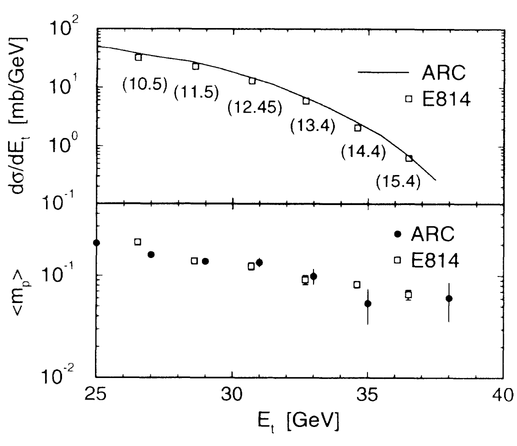

FIG. 3. E_t distributions of total cross section and forward protons $\langle m_p\rangle$. Forward protons are defined to be those protons in the region $y_L > 3.0$ and $|\theta_x| \le 18.7$ mrad and $|\theta_y| \le 12.0$ mrad [3]. The radii of the nuclei are determined from electron scattering with the simplification $R_n = R_p$. Theory and experiment are compared at equal values of the integrated cross section $\int_{E_t}^{\infty} dE_t (d\sigma/dE_t)$. This leads to a correction factor of approximately 2.4 in $E_t^{\rm ARC}/E_t^{\rm E814}$, which is presumably due to the leakage of the detectors [3]. The original E_t values of the E814 data are listed below the points in the top panel. The theoretical $\langle m_p\rangle$ has been corrected for cluster production (see text).

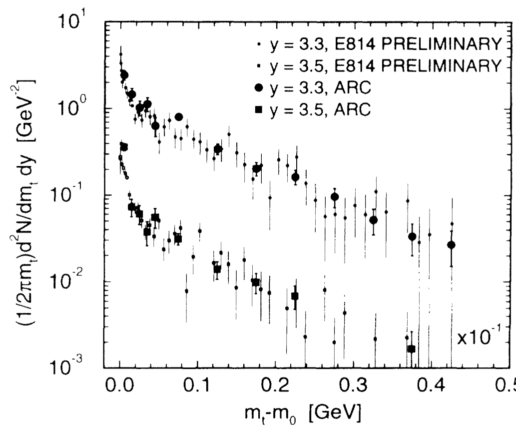

FIG. 4. Transverse mass distributions of protons in rapidity bins $y=3.3$ and 3.5 for ARC and E814 preliminary data [4]. The $y=3.5$ data are multiplied by 10^{-1} for clarity. The agreement with detailed m_t distributions in both magnitude and shape for these most forward bins speaks very well for the validity of cascade dynamics.

lision. A consistency in fact now exists between the observations by E802 [6] of energy transferred to mesons and to target nucleons and by E814 of energy lost from projectile particles. The high degree of accuracy achieved by our essentially parameter-free simulation for a broad range of rapidity lends great credence to its future application to collisions initiated by more massive projectiles and perhaps at higher energies. In preliminary work for Au on Au we find baryon densities rising to higher levels and sustained for longer periods of time than seen with Si. It will be interesting to see whether or not deviations from the cascade predictions obtain experimentally, signaling the presence of interesting collective effects.

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