Energy and Baryon Flow in Nuclear Collisions at 15*A* GeV

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(Received 28 May 1991)

Strong correlations between baryon stopping in the projectile rapidity hemisphere and target excitation have been found in the light-ion-induced reactions at the BNL Alternating Gradient Synchrotron (AGS) (E814 group). Results in the framework of the relativistic molecular dynamics approach (RQMD) describe recent E814 data quite well. We discuss the RQMD results together with proton and pion data from the E802 group near midrapidity. They have raised the question of whether partial transparency could be seen in these AGS experiments. The RQMD results indicate strong transverse baryon flow in central Si+Au collisions after the projectile has been stopped in the target.

PACS numbers: 25.75.+r, 24.10.−i

The BNL Alternating Gradient Synchrotron (AGS) energy region [(10–15)*A* GeV] is thought to be very promising to achieve nuclear stopping and a high degree of thermalization [1,2] which are key variables for the formation of hot, dense matter far beyond the ground state. There are two main arguments for this belief. The initial rapidity gap of three units between projectile and target might be filled during the first interpenetration stage of central collisions, because in high-energy proton collisions on heavy nuclei a projectile loses up to two units in rapidity [3]. Secondly, a formation time of produced secondaries which is on the order of 1 fm/*c* means that most of the secondaries are born inside the heavy target in the BNL experiments. Global observables like transverse energy production seemed to be compatible with the picture of nearly complete projectile stopping at AGS [4]. However, recent E802 measurements of protons and pions near midrapidity ($y = 1.7$) [5] indicated surprisingly low particle yields in this momentum region, which can only be reconciled with energy-momentum conservation [6,7] if the Au target is rather transparent for a large fraction of the Si projectile.

In the following we study the flow of energy-momentum and baryon number in the framework of the relativistic quantum molecular dynamics (RQMD) approach [8], a microscopic model for the nucleus-nucleus dynamics in phase space. In earlier calculations we predicted strong stopping and density pileup [1] for the current light-ion-induced reactions at 14.5*A* GeV. Now we compare the RQMD results with recent measurements done by the E814 group at the AGS. The E814 experiment covers parts of the target and projectile fragmentation regions [9] and therefore gives independent information about the final state—in addition to the E802 midrapidity data.

In the Lorentz-invariant microscopic phase-space approach of RQMD one follows the trajectories of all hadrons (including the produced particles). RQMD combines the classical propagation of the hadrons with stochastic scattering and decay of unstable hadrons. Pions and other mesons are not directly produced, but result from the decay of excited resonances and hadronic strings which are produced in inelastic collisions. The space-time structure of the dynamics is completely fixed by the momentum space properties of the resonances and the strings. The formation time of newly produced secondaries is given by the finite lifetime of either a resonance or a string before breaking, which is related to the momenta of the fragments.

In Fig. 1 we show a comparison of RQMD results —done for central Si+Au collisions—and E814 measurements (for Si+Pb) of the transverse energy production in the target region. (We took an Au target instead

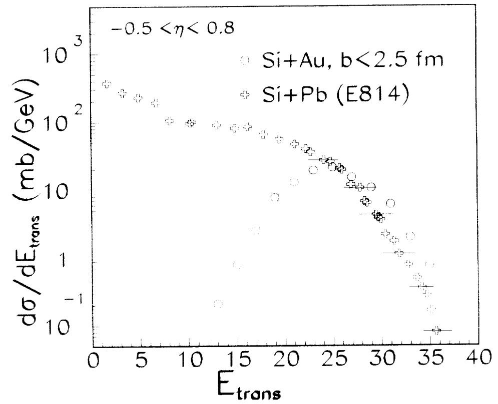

FIG. 1. Differential cross section for transverse energy production in a backward pseudorapidity interval $-0.5 < \eta < 0.8$. The transverse energy is defined as $E_{\mathrm{trans}} = \sum E_i \sin(\theta)_i$, with E_i the kinetic (total) energy for each baryon (meson). The RQMD calculation (circles) for central Si(14.6*A* GeV)+Au events is compared with E814 measurements for the reaction Si+Pb. The experimental data (crosses) are corrected for the "leakage factor" = 2 [9]. It has been fixed as the average of the leakage factors for the Landau fireball model and the HIJET cascade (indicated by the error bars) which have been determined by E814.

of Pb, because later on we will compare to E802 Si+Au measurements, but we expect that the difference between these targets will be small.) The maximally produced transverse energy seen in the experiment can be reproduced very nicely by RQMD. Most of the produced transverse energy in this backward window in pseudorapidity ($-0.5 < \eta < 0.8$) is carried by target nucleons. Therefore the transverse energy in this phase-space region measures the degree of excitation of the target by the impinging projectile. In the calculations we observe multiple scattering of the projectile nucleons and produced secondaries in the target. The total collision number (more than 800) exceeds the numbers estimated from simple Glauber-type approaches by a factor of 5.

In Fig. 2 we follow the procedure of the E814 group and show the neutron rapidity distribution in the projectile hemisphere ($y > 2$) for events in the bin of maximum backward E_{trans} production corresponding to a cross section of 40 mb. Unfortunately the experimental setup allows only for the detection of neutrons in a very restricted angular cone around the beam axis ($\theta < 0.8°$). The most important result is that essentially no neutrons are left over near the original projectile rapidity—in the data as well as in the RQMD calculations. We find that the neutron peak around $y = 3.4$ represents the spectator neutrons which did not suffer any collision (~0.03 per event). The agreement between experimental data and RQMD results over the whole rapidity range is quite good. In contrast to other calculations—with the HIJET cascade and the Landau fireball [9]—the shape of the neutrons in the RQMD results and in the experimental detector are very similar. The neutron distribution in the rapidity range $2.5 < y < 3$ which is sensitive to the transparency of the gold target and the "fireball" dynamics is strongly influenced by the angular cutoff. Only 3% of all neutrons in this rapidity region are inside the acceptance window as calculated by RQMD. For future use we note that the RQMD calculations give a total of 2.6 nucleons in this rapidity region. If scaling from the acceptance window to the whole rapidity region is allowed we therefore expect at most 5 nucleons with rapidities between 2.5 and 3 from the upper limit of the experimental error bars.

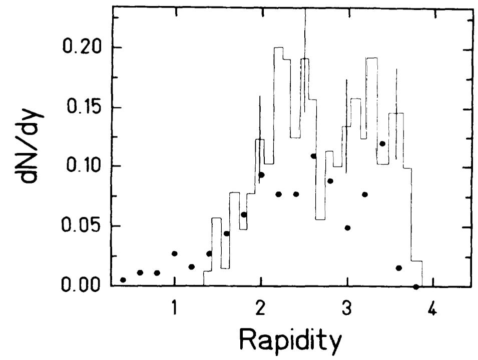

FIG. 2. Neutron rapidity distribution in central Si(14.6*A* GeV)+Au collisions in the acceptance window $\theta < 0.8°$. The RQMD results (circles) are compared to E814 data (histogram) for Si+Pb events with maximum backward transverse energy production ($\sigma = 40$ mb).

In Fig. 3 we show the calculated proton and π^+ rapidity distributions for the reactions p+Be, p+Au (minimum bias), together with central Si+Au reactions at a beam energy of 14.5*A* GeV. Minimum-bias p+Be interactions resemble more or less individual nucleon-nucleon collisions because of the low mass of the target. The calculated proton distribution shows indeed that the projectile is not stopped in the target, but a second maximum near the original projectile rapidity persists in the calculations. A second maximum seems also to be present in the experimental data (E802) which are shown in the same figure. In the p+Au case, however, the second maximum in the proton rapidity distribution has disappeared. Instead we see a broad plateau, which is characteristic also for RQMD $p+A$ calculations at

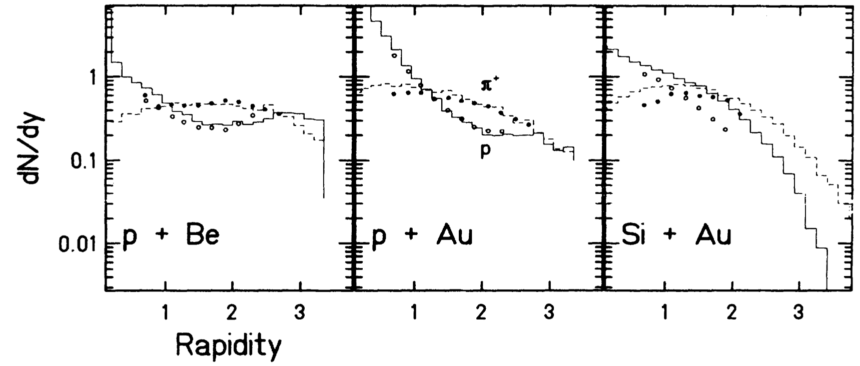

FIG. 3. Calculated and experimental meson rapidity distributions for minimum-bias p+Be (left), p+Au (middle), and central Si+Au (right) reactions at a projectile energy of 14.5*A* GeV. The histograms represent the RQMD results: protons (solid lines) and π^+ (dashed lines). The experimental data are shown for protons as open circles and for π^+ as solid circles. The Si+Au distributions are divided by 28.

higher beam energies [1] and experimentally already confirmed at 24 and 100 GeV. Note that the pion number in the projectile hemisphere ($y>2$) is larger for $p+\mathrm{Be}$ than for $p+\mathrm{Au}$. This demonstrates that even the fast pions undergo rescattering before leaving the heavy target.

If we look at the proton rapidity distributions we see that the RQMD calculations show an enhancement of projectile stopping in Si+Au compared to $p+\mathrm{Au}$. There is no longer a plateau at forward rapidity. If we compare the E802 proton data for $p+\mathrm{Au}$ and Si+Au one notices that they seem to be rather identical in the rapidity range under experimental consideration, and they are much smaller for Si+Au than the corresponding RQMD results. The difference in the proton and—to a smaller extent—in the pion distributions between RQMD and E802 data represents energy and momentum which has to be carried by other particles or in other parts of the momentum space. The authors of [7] estimated that—at least—11 of the 28 incident nucleons have to be in the rapidity interval $2.5<y<3.0$ to account for all the incident momentum. However, as stated above, the E814 measurements do not favor such a large number of nucleons at these high rapidities but at most half of them if the extrapolation to higher transverse momenta is the same as in RQMD. We would like to mention that the problem of the "missing" energy-momentum could be resolved if the normalization of the E802 spectrometer data were too small. The independent charged-particle multiplicity measurement by the same experimental group points towards a systematically higher multiplicity (on the order of 20%) [10]. A further confirmation of higher charged-particle pseudorapidity distributions than indicated by the spectrometer results has been obtained by E814 for the similar system Si+Pb [9].

As a further possibility, the missing energy-momentum could be contained in the transverse degrees of freedom. In Fig. 4 we show a comparison of transverse mass spectra at $y=1.3$ between RQMD and E802 data. The RQMD calculations were done with quasipotential interaction between the baryons included [8]. We used Skyrme-type potentials giving strong repulsion at high densities. The repulsion in an excited baryon resonance gas is not well determined. In order to get good agreement with the proton slope of the E802 data the attractive part of the quasipotentials between NB and DD ($N=$nucleons, $D=\Delta$, $B=$other baryon resonances) was switched off. The slope parameters T in an exponential fit to the RQMD distribution in the transverse momentum region $0.3<p_t<0.9$ GeV [221 MeV (protons), 166 MeV (pions), and 214 MeV (kaons)] are in accordance with the experimental findings [5]. In Fig. 5 we show the influence of the repulsive quasipotentials by switching them off (cascade mode of RQMD). While the pions are less affected by the pressure-induced flow the protons clearly exhibit the presence of strong pressure due to the quasipotentials. If confirmed by future measurements—eventually of even higher mass particles like deuterons—the analysis of the p_t spectra might become a very useful "baryometer" in nucleus-nucleus collisions at AGS.

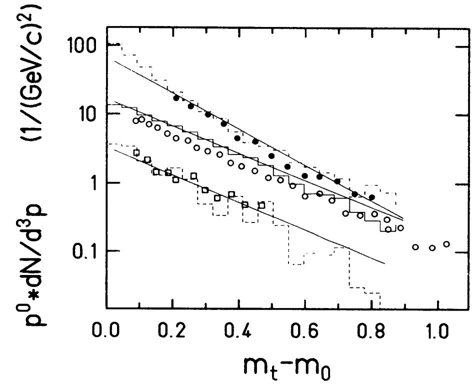

FIG. 4. Calculated and experimental transverse mass spectrum for positively charged particles in central Si+Au at 14.5A GeV. The rapidity range is $1.2<y<1.4$. The histograms represent the RQMD results for p (solid line), π^+ (dash-dotted line), and K^+ (dashed line). The symbols denote the E802 data: open circles (p), solid circles (π^+), and squares (K^+). In addition an exponential fit to the RQMD results is shown which clearly demonstrates the different apparent "temperatures."

One might think of other possibilities than repulsive mean fields for an explanation of the large proton slopes, dense matter effects like, for instance, pion absorption and modified cross sections. Pion absorption on nucleons increases their kinetic energies and influences therefore the transverse mass spectra. Pions can be absorbed in RQMD simulations, because we always use detailed balance for binary collisions. The most important channel for pion absorption in the resonance region is $\pi+N\rightarrow\Delta$, $\Delta+N\rightarrow N+N$. We improved the naive detailed balance model by taking into account that the Δ is unstable and

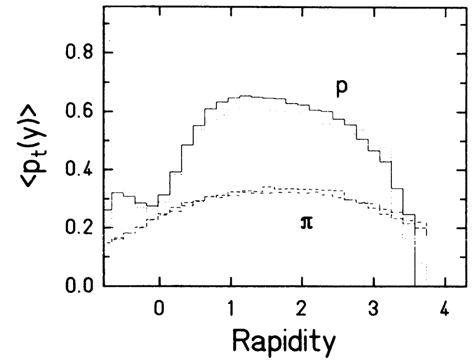

FIG. 5. Mean transverse momentum for protons and pions as a function of rapidity. RQMD calculations with (solid-line and dashed-line histograms) and without quasipotential interaction (dotted-line and dash-dotted-line histograms) are compared for central Si+Au collisions.

has a smeared mass. We will show in a forthcoming publication that this effect leads to an order-of-magnitude difference in absorption of pions on nuclei at Δ resonance energy. However, this effect is strongly energy dependent: With the improved detailed balance pion absorption—including channels like $\Delta\Delta \rightarrow NN$—our finding is that only roughly 30 pions are absorbed in central Si+Au collisions (to be compared to about 190 final pions). Cutting off the pion absorption totally increases the total pion yield by only ~15, because absorption converts the pion energy into kinetic energy which is subsequently available for particle production. Therefore the final pion yields and hadron spectra are only marginally affected by pion absorption. We also tested the influence of the angular distributions in the elementary collisions on the final spectra, because the total magnitude of the cross sections as well as the angular distributions might change considerably in dense matter. Despite making the angular distributions isotropic we were not able to reproduce the measured proton slopes. The final hadron distributions were completely insensitive to this change, which indicates that the "thermal" part of the pressure is not sufficient to describe the total buildup of transverse momenta.

In conclusion, the recent AGS experiments with silicon projectiles have opened up the possibility to study highly compressed and excited nuclear matter. *If* the baryons are really stopped and *if* they experience collective flow at a beam energy around 15 GeV, heavy-ion collisions at such beam energies might be of utmost importance for an extraction of the nuclear equation of state. However, up to now the key mechanisms of the reaction dynamics are not really well determined. The question of the "missing" energy-momentum remains puzzling. We have to await future experiments at AGS in which independent setups have some overlap in acceptance.

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