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Evidence for a Blast Wave from Compressed Nuclear Matter

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ABSTRACT

Central collisions of heavy nuclei at c.m. kinetic energies of a few hundred MeV per nucleon are expected to lead to the formation of a fireball of hot, dense nuclear matter. We argue that such a fireball would be expected to explode, leading to a blast wave of nucleons and pions. The energy for the blast wave comes from the compressional and thermal energy of the fireball. We show how several features of the observed inclusive cross sections for pions and protons from Ne on NaF at 0.8 GeV/nucleon(lab) can be understood in terms of the blast wave, but are incompatible with earlier, purely thermal models. About 40% of the available energy appears as translational kinetic energy of the blast, with a similar amount ending as thermal motion of the nucleons in the exploding matter (the remainder is used for pion creation). This partitioning of the energy into organized and thermal motion can be used to help determine properties of the hot, dense matter.

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One of the principal motivations for accelerating heavy-ion beams to relativistic energies is the hope of producing and studying matter at baryon densities greater than are found in atomic nuclei. However, information about the properties of the dense matter thus created is obscured by three major dynamical consequences of the high energies needed to get high densities: First, the high-density region (the nuclear fireball) may not include all the nucleons from the target and projectile[1]. Second, the high-density matter must be in a state of high excitation, so we must use the data to infer not only the density but also the distribution of the excitation energy among the matter's internal degrees of freedom[2]. Third, the compressed matter remains hot and dense only for a very short time $<10^{-22}$ s., and our observations are limited to the products emitted as it disassembles. We present arguments that the observed pions and protons do not exhibit the simple, thermal distributions assumed by the earlier "fireball" and "firestreak" models[1,3]. Rather, we show how several features of the observed cross sections may be understood as typical of the blast (pressure wave) produced by the explosion. We use these features to estimate the speed of the blast wave, and find (for Ne on NaF at 800 MeV per nucleon laboratory kinetic energy) that about half the available energy appears as translational kinetic energy of the blast, while a similar amount ends up as thermal agitation of the particles in the exploding matter. Finally, we suggest how information on this partitioning of energy into organized and thermal motion may help to determine properties of the dense matter.

It is a matter of ordinary experience that the sudden creation of hot dense matter leads to an explosion (bombs, blasting caps, supernovae). The blast wave of the explosion is a result of frequent collisions of the rapidly-moving particles in the hot matter: particles just inside the surface of the high-density region will be able to move outward freely, while those with inward motion will be deflected by collisions with the hot, dense matter inside. Thus particles on the surface will soon be moving outward, on the average: the anisotropy in their environment gives rise to an anisotropy in their velocity distribution, and the kinetic energy of their motion becomes less random. In this way the particles acquire a net flow velocity β, the blast wave, the energy for which comes primarily from the kinetic energy of their random relative motion. As they move outward, they fill more space, so the density decreases in the surface, and the next layer of particles inside the surface now experiences an anisotropic environment and also begins to move outward.

A convenient quantitative description of this phenomenon, in the limit of very frequent collisions, is provided by hydrodynamics(2): one says that the matter locally acquires an outward-directed macroscopic flow velocity β by converting internal thermal energy into work through a pressure gradient $\vec{\nabla}P$. The force $-\vec{\nabla}P$ is conservative (i.e. reversible), so that entropy is conserved during the expansion: the additional phase-space exploited by the expansion of matter into a larger region of position space is compensated by the concentration of the velocity distribution into a narrower region of momentum space, as the cooling of the matter provides the energy for the macroscopic flow. Entropy is produced only by diffusion of particles between neighboring regions of different mean velocity (viscous forces) or different internal energy (thermal conduction), both expected to be small (The rate of entropy production by thermal conduction is proportional to the square of the thermal gradients, while viscous forces may be large only if large shear velocities are present due to incomplete thermalization of the original kinetic energy of relative motion). Additional energy for the blast may be provided by the elastic forces between the nucleons, whose compressional energy is released as the density falls, and by the reabsorption of pions and deexcitation of nucleon resonances as the temperature falls.

This conversion of thermal and compressional energy E^* into organized blast-wave flow continues as long as collisions are sufficiently frequent. Eventually the density becomes so small that the particles no longer collide and instead retain their momenta until they reach the detectors. Thus the final distribution of momenta will be characterized by a mean expansion velocity β, and a fluctuation about the mean β due to the remaining intrinsic excitation E^*. The characteristic features of the explosion are

(a) the peaking of the observed velocity distribution about the mean radial velocity β, in contrast to the fully thermalized distribution which is largest for the slowest particles in the fireball frame, and

(b) the reduction of the intrinsic excitation due to the cooling accompanying the expansion.

To look for these signs of the exploding fireball, we have analyzed the reaction of 800 MeV per nucleon Ne with a NaF target. We choose a symmetric target-projectile combination because then the rest frame and intrinsic excitation of the fireball are independent of the impact parameter (in a clean-cut geometry[1]), and because the explosion will occur in free space instead of inside the target nucleus. To maximize multiple-collision effects, we choose the heaviest beam for which comprehensive data are available for both pions and protons (a heavier beam would be preferable). A high energy is chosen to maximize pion cross sections (as well as the anticipated compression); we hope that 800 MeV per nucleon is not so high that transparency becomes a problem[2]. An added advantage of the high excitation energy is that it reduces the relative importance of Coulomb forces, nuclear binding and Fermi/Bose statistics. To minimize background from projectile and target fragmentation, knock-on scattering and pion production[4], and shadowing by target and projectile fragments, we concentrate our attention on the spectra of pions and protons at 90° in the c.m., shown in the figure.

Inspecting the logarithmic slopes of the distributions at large transverse kinetic energy, we see immediately that both pions and protons are much cooler than would be expected if the full initial kinetic energy of 182 MeV per nucleon were retained in thermal motion. Only part of this cooling is due to pion production: in the distributions shown, there is about one pion for every 10 protons; with a mean pion energy of about 240 MeV (including rest mass), and assuming equal numbers of $\pi^{\pm}$ and π^{o}, about 35 MeV per baryon has gone into producing and accelerating pions, so the temperature would be about 90 MeV if all the remaining energy were in thermal excitation. We tentatively attribute the additional cooling to the production of a blast wave.

The other characteristic feature of the explosion, the peaking of the velocity distribution, is less apparent in the measured inclusive spectra. In the case of the π^+ spectra, the peak in $d^3\sigma/dp^3$ around 15 MeV pion kinetic energy appears suggestive, but is probably produced by Coulomb effects[7]. We believe it is only accidental that this peak is near the blast velocity. A comparison of π^+ and π^- cross sections at low energy in the c.m. would confirm the Coulomb nature of the peak in the π^+ spectrum: the π^- spectrum at 90° c.m. should not show such a peak, but should be largest for the smallest c.m. kinetic energy.

The measured proton spectum begins at c.m. energies too large for Coulomb effects to be significant. Also, for protons, the rms thermal velocity will be smaller than it is for pions at the same temperature, so the peaking of the proton distribution at the blast velocity should be more pronounced. The measured inclusive spectrum does exhibit a slight shoulder, but this may be obscured by the presence of knock-on protons at moderate momentum transfer ($E_{cm}(\mathrm{proton})<E_{cm}(\mathrm{beam})/A$). Indeed, the low-transverse-momentum cross section is suppressed relative to high transverse momenta if high charge multiplicity is used to select central collisions[8]. Thus we expect a surplus of low-transverse-momentum protons from knockout reactions to be added to those from the fireball.

To gain a more quantitative understanding of these spectra, we can try to fit them with a simple model. Consider a spherically symmetric fireball expanding to a radial velocity β and a temperature T. Then the momentum-space density of particles of momentum p and energy E is given by[9]

$$\frac{d^3n}{dp^3} = N \frac{\exp(-\gamma E/T)}{Z(T)} \left[(\gamma + \frac{T}{E})\frac{\sinh \alpha}{\alpha} - \frac{T}{E} \cosh \alpha \right] \qquad (1)$$

where $\gamma=(1-\beta^2)^{-\frac{1}{2}}$, $\alpha=\gamma\beta p/T$, and Z(T) is the normalization of a relativistic Boltzmann distribution of temperature T. For large p, this distribution resembles a Boltzmann distribution with the apparent temperature $T_{app} = (-d \ln \sigma/dE)^{-1} \simeq T\gamma^{-1}(1-\beta E/p)^{-1}$. Thus the pions ($p \approx E$) should appear cooler than the protons ($p<E$), as is indeed seen. The figure shows a fit of eq. 1 to the high-energy parts of the proton and pion spectra (c.m. kinetic energy > beam energy per particle). The fitted parameters were the normalizations of the pion and proton spectra, and the common temperature. The blast velocity was determined by requiring the mean kinetic energy of the fitted proton distribution to be equal to the beam energy per particle minus the energy of the pions, assuming $\sigma(\pi^+)=\sigma(\pi^-)=\sigma(\pi^o)$ and $\sigma(n)=\sigma(p)$.

We see that the evidence for the blast wave in the inclusive spectra is inconclusive, though suggestive. This may be due to the small number of nucleons in the fireball, and we would expect to see a clearer picture in collisions with heavier nuclei. Indeed, Monte Carlo studies suggest that the Ne + NaF system is too small for multiple collisions to be very important[10];if evidence is seen here, it may be an indication that pion exchange is enhanced in dense nuclear matter, as suggested by Gyulassi[11]. The signs of the blast wave should also become more prominent if central collisions are selected by e.g. a multiplicity trigger: a preliminary analysis of proton spectra selected in this way shows a much more pronounced shoulder in the proton distribution at 90° c.m. for Ar + KCl at 800 MeV per nucleon[8].

We may remark that the shoulder in the proton spectra is in qualitative disagreement with the firestreak model[3], in which the superposition of thermal distributions of varying temperatures leads to a distribution of transverse kinetic energies that would be concave upward in the figure. The firestreak model accounts for the low transverse temperature by retaining some of the initial kinetic energy in longitudinal motion, while the data show that at least some of this energy must be in the transverse motion.

We would not contend that the data for neon beams prove the validity of the picture of an explosion starting from equilibrated hot matter. What we do stress is that proton and pion distributions at 90° c.m. are not simply thermal. There are alternative interpretations based on microscopic collision models to account for the paucity of slow pions and protons in the c.m. If we neglect Fermi motion, the initial scattering of two nucleons changes directions but leaves them each with their original c.m. kinetic energy. Subsequent collisions as well as Fermi motion act to modify the distributions toward a thermal limit. Likewise, at 800 MeV/N the pions may be visualized as born from decay of an N*(1238) nearly at rest in the c.m., hence born with about 130 MeV kinetic energy. Scattering with nucleons modifies the pion distribution toward a thermal limit. However, it is unusual in a few-collision picture that the pions and protons indicate a common collective (blast) velocity. In addition, our picture unifies the non-thermal features of the high- and low-transverse-momentum parts of the spectra.

Whether or not the blast-wave interpretation of the neon data is ultimately upheld, there is real hope that for heavier projectiles the hydrodynamic picture may be realized for the hot compressed matter. Then the observed temperature allows one to infer the total entropy of the high-density matter, provided we also know the density at which collisions cease, which may be estimated from the production of light nuclei[12]. The entropy of the initially compressed matter is sensitive to its equation of state: the entropy will vary inversely with the strength of repulsive forces between baryons, and it will increase if baryon resonances and mesonic degrees of freedom come into play. Thus we believe that the identification of the blast wave from exploding fireballs is an important step toward learning about the properties of dense hot baryonic matter.

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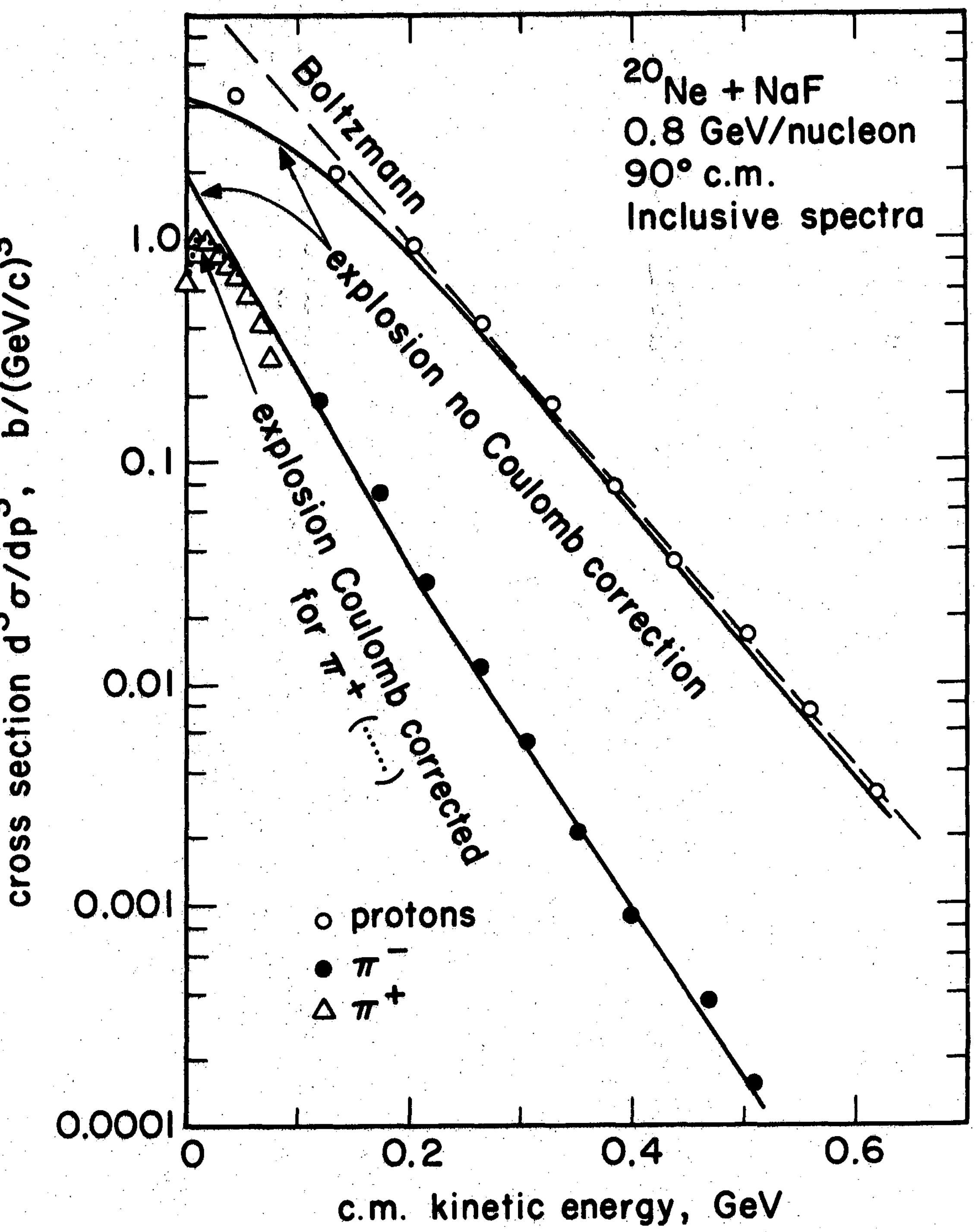
Figure caption

Inclusive cross sections $d^3\sigma/dp^3$ at 90° in the c.m. for Ne on NaF at 800 MeV per nucleon laboratory kinetic energy. o protons, ● π^- from ref. 4; Δ π^+ from ref. 5. Solid lines: expanding fireball (text, eq. 1) fit to data for c.m. kinetic energy > E_{beam}/A =0.182 GeV, with T=44 MeV, β=0.373, $N(\pi^+)$=0.094N(proton). The dashed curve is a Boltzmann distribution extrapolated from the high-energy proton cross section. The dotted curve is the expanding fireball expression for π^+ roughly corrected for Coulomb effects by the factor $[F_o^2 + G_o^2]^{-1}$, evaluated for s-wave π^+ with the full nuclear charge and radius of the combined ${}^{40}_{20}Ca$ system.



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