Evidence for a Blast Wave from Compressed Nuclear Matter

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Central collisions of heavy nuclei at c.m. kinetic energies of a few hundred MeV per nucleon produce fireballs of hot, dense nuclear matter. Each fireball explodes, producing a blast wave of nucleons and pions. Several features of the observed cross sections for pions and protons from Ne on Na F at 0.8 GeV/nucleon (lab) are explained by the blast wave, but contradict earlier, purely thermal models. The available energy is equally divided between translational energy of the blast, and thermal motion of the paritlces in the exploding matter.

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, and 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, purely 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 ∇P. The force $-\nabla P$ 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 by 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. system, shown in the Fig. 1.

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 distribution shown, there is about one pion for every ten protons; with a mean pion energy of about 240 MeV (including rest mass), and assuming equal numbers of $\pi^\pm$ and π^0, about 35 MeV per baryon has gone into producing and accelerating pions, so that 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.

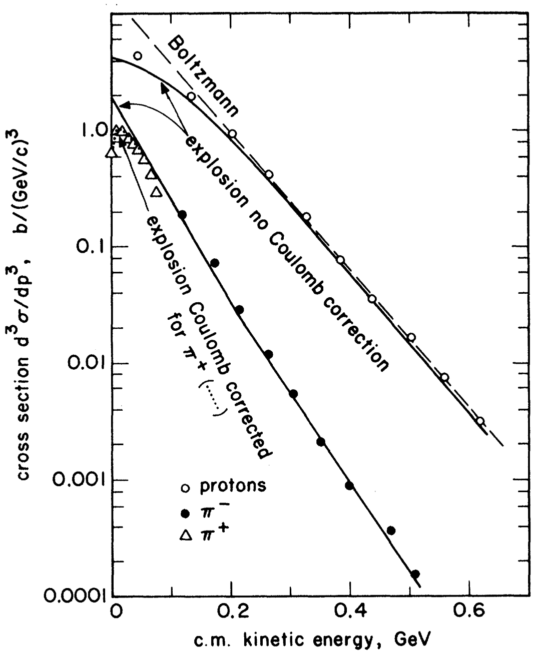

FIG. 1. Inclusive cross sections $d^3\sigma/dp^3$ at 90° in the c.m. system for ^{20}Ne on NaF at 800 MeV per nucleon laboratory kinetic energy. Open circles, protons; closed circles, π^- from Ref. 5; triangles, π^+ from Ref. 6. Solid lines: expanding fireball [text, Eq. (1)] fit to data for c.m. kinetic energy $> E_{\mathrm{beam}}/A = 0.182$ GeV, with $T = 44$ MeV, $\beta = 0.373$, $N(\pi^\pm) = 0.094N(\mathrm{proton})$. 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 $[F_0(\eta,\rho)^2 + G_0(\eta,\rho)^2]^{-1}$, evaluated for s-wave π^+ with the full nuclear charge and radius of the combined $^{40}_{20}$Ca system. F_0 and G_0 above are, respectively, the standard regular and irregular Coulomb functions, with η the Sommerfeld parameter and ρ $(=\kappa R)$ the dimensionless radial coordinate.

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. system 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 spectrum 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 [$E_{\rm c.m.}$(proton) $<E_{\rm c.m.}$(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. Bondorf, Garpman, and Zimayni[9] have derived their Eq. (8) to express nonrelativistically the energy distribution. We have generalized this relativistically to give the following expression for the final momentum-space density of particles of momentum p and energy E:

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

where $\gamma=(1-\beta^2)^{1/2}$, $\alpha=\gamma\beta pT$, $Z(T)$ is the normalization of a relativistic Boltzmann distribution of temperature T, and N_i gives relative normalization of pions and protons.

We assume that pions are in kinetic equilibrium with the nucleons, attaining a common temperature T and flow velocity βc, but pions are not assumed necessarily in chemical equilibrium. The figure shows a fit of Eq. (1) to the high-energy parts of the proton and pion spectra with (c.m. kinetic energy greater than beam energy per particle). The fitted parameters were the normalizations of the pion and proton spectra, blast velocity βc, and the common temperature. The parameters are constrained by total energy conservation, requiring the mean proton kinetic energy (thermal plus ordered flow) plus the energy in pion mass to be equal to the beam energy per nucleon in the center-of-mass system. Unobserved particles (n, π^+, π^0) are included by assuming complete isobaric symmetry, i.e., $n_{\pi^+}=n_{\pi^0}=n_{\pi^-}$ and $n_n=n_p$. For large p, this distribution resembles a Boltzmann distribution with the apparent temperature $T_{\rm app}=(-d\ln\sigma/dE)^{-1}=T\gamma^{-1}(1-\beta E/p)^{-1}$. Thus the pions ($p\approx E$) should appear cooler than the protons ($p<E$), as is indeed seen.

Monte Carlo studies suggest that the Ne + NaF system is too small for multiple collisions to be very important[10]; thus, this evidence for a blast feature may be an indication that pion exchange is enhanced, and the effective nucleon mean free path shortened in dense nuclear matter, as suggested by Gyulassi and Greiner.[11] The signs of the blast wave should become more prominent if central collisions are selected by 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 notion.

The departure from complete equipartition of energy due to the ordered motion of the blast has especially interesting implications for the spectra of composite light nuclei (d, t, etc.). In the coalescence model[12] these composites are formed after the nucleon velocity distribution has reached its asymptotic value, and the spectrum is that of a proton raised to the power of the mass number of the composite. If, on the other hand, the velocity distribution of composite is kinetically equilibrated after formation, then its distribution will be given by our Eq. (1). These two contrasting conditions lead to the same apparent temperature in the asymptotic region, but the spectra differ especially in the vicinity of the blast velocity.

Thus, it is of great interest to have available reliable spectra of composite particles with which to test further the blast picture.

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. 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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[7]The Coulomb penetration factor for a pion of 15 MeV at the surface of the compound nucleus ($Z=20$, $A=40$, $r_0=1.25$ fm) is 0.80, 0.48, and 0.12 for $L=0$, 1, 2; for twice the volume, the factors are 0.83, 0.59, and 0.23, respectively. The rms angular momentum of the pions in the model described in the text is about $1.0\hbar$ and $1.25\hbar$ for the smaller and larger volumes, respectively.

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[9]J. P. Bondorf, S. I. A. Garpman, and J. Zimanyi, Nucl. Phys. A296, 320 (1978). The assumption of spherical symmetry by them and by us could be questioned if the fireball were confined by large pieces of spectator matter; however, the form of our Eq. (1) would not be altered so as to affect the qualitative conclusion of a hydrodynamic explosion. Note that these authors go on to express their final distributions [their Eq. (9)] as an integral over the expanded fireball having elements with varying temperature and flow. In view of the complexity of the freeze-out density question we believe our use of the simpler single-temperature expression is justified.

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Ab Initio Calculation of Hyperfine and Magnetic Parameters in the I_2 B State

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A simple analytic calculation of magnetic and hyperfine constants of molecular iodine in the $B\,{}^3\Pi_{0^+u}$ state is carried out. The calculation is based on simple physical ideas which are well suited to represent precisely molecular states close to their dissociation limit. Thus the method is quite general. The agreement between theory and experiment for the I_2 B state is good.

During the last ten years, a large number of sub-Doppler spectroscopic measurements have allowed determination of accurate values of the hyperfine[1,2] and magnetic constants[3,4] in the B state of molecular iodine. Although some of these constants (spin rotation C_I; rotational Landé factor g_J; and chemical shift g_1) exhibit large variations with energy levels, only rough models[1,3] have been given to explain these changes.

