

Pion and Proton "Temperatures" in Relativistic Heavy-Ion Reactions

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Pion and proton production are measured to investigate thermal equilibrium in central collisions of $^{40}\text{Ar} + \text{KCl}$ at 1.8 GeV/nucleon. The bulk of the pion yield is isotropic in the c.m. system, with an apparent temperature of 58 ± 3 MeV, much lower than the 118 ± 2 MeV of the protons. It is shown that the low pion "temperature" can be explained by the decay kinematics of delta resonances in thermal equilibrium. A $(5 \pm 1)\%$ component in the pion spectrum is, however, found to have a temperature of 110 ± 10 MeV. The effect on the spectra of possible contributions from collective radial flow is discussed.

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An understanding of pion production in relativistic heavy-ion collisions is needed for several reasons. Firstly, it is the predominant production process at Bevalac energies. Secondly, pion production has been suggested as a probe of the compressional energy in the high-density phase of near head-on collisions.^{1,2} Thirdly, a comparison between pion and proton energy spectra has been suggested as a method of identifying the presence of collective flow effects in the expanding nuclear system.³⁻⁵ Previous experimental studies of the pion spectra have been for inclusive measurements only.⁶ Attempts have been made to fit the results with a variety of hypotheses, including collective flow,³⁻⁵ pion absorption,⁷ and different thermal freezeout times for the pions and protons.⁸ The most successful method has been the intranuclear cascade model^{9,10} based upon Δ dominance in the production mechanism. In the present experiment we have used a central-collision trigger to provide a well-defined collision geometry as close to an idealized "fireball" as possible, and to eliminate complications such as spectator-matter effects. The pion and proton energy spectra are found to be close to

Boltzmann-type temperature distributions, but with very different effective temperatures. We find that the results can most simply be described by the decay kinematics of Δ resonances in thermal equilibrium, confirming the Δ dominance assumed in the intranuclear-cascade calculations which fit the data quite well. However, we find that the comparison of pion and proton spectra does not give sufficient accuracy for determining contributions from collective flow, without further assumptions.

The Lawrence Berkeley Laboratory streamer chamber facility was used to study central collisions of $\text{Ar} + \text{KCl}$ at 1.8 GeV/nucleon, for which the total π^- yields and proton flow distributions have previously been reported.^{11,12} The experimental procedures are described in Sandoval *et al.*¹³ Events were selected to correspond to impact parameters of less than 2.4 fm. It has been found by exclusive measurements of the protons¹² that in such events the central higher-density parts of the interacting nuclei (as seen along the beam direction) stop in each other and decay isotropically, while nucleons in the nuclear peripheries often do not undergo enough collisions to be equilibrated. The latter

“corona effect” must be borne in mind when considering the present data. The invariant π^- production cross section in the c.m. system was measured as a function of pion kinetic energy E and angle θ , and fitted with the expression

$$\frac{1}{p} \frac{d^2\sigma}{dE d\Omega} \propto \sigma(E) [1 + a(E)\cos^2\theta]. \quad (1)$$

The pion yield as a function of the c.m. angle θ follows from an energy average of both sides of (1),

$$\frac{d\sigma}{d\cos\theta} \propto (1 + a \cos^2\theta). \quad (2)$$

The inset in Fig. 1(a) shows the distribution $d\sigma/d\cos\theta$ and a fit with Eq. (2), where $a = 0.52$. After integration over $\cos\theta$ the ratio of the angle-dependent component to the total is found to be $\alpha = a/(a + 3) = 0.15$. This fairly low degree of an-

isotropy in central collisions at the top Bevalac energy has to be compared with anisotropies of $\alpha \geq 0.50$ characteristic of individual $NN \rightarrow NN\pi$ collisions at similar energies.¹⁴

A closer inspection of the kinetic energy dependence of the anisotropy is possible through the functions $\sigma(E)$ and $a(E)$ defined by Eq. (1) and shown in Figs. 1(a) and 1(b), respectively. Staying near zero for $E < 100$ MeV, $a(E)$ rises to a peak at $E \approx 300$ MeV where $\alpha = 0.45$, and then falls again to $\alpha < 0.20$ at $E > 400$ MeV. Figure 1(a) shows that about 70% of the yield falls in the first interval, $E \leq 100$ MeV, with complete isotropy. The major fraction of the overall anisotropy is contributed by the yield at $100 \leq E \leq 350$ MeV, which is about 25% of the total. The remaining 5% of the yield, at $E > 350$ MeV, tends towards isotropy at the highest energies. Somewhat similar results⁶ have been reported in inclusive pion data for Ar + KCl at 0.8 GeV/nucleon, but with a higher overall degree of anisotropy, resulting from the contribution of larger impact parameters to those data. The latter conclusion is reached by studying minimum-bias data obtained at 1.8 GeV/nucleon (not illustrated here) where we find a smooth falloff in the overall anisotropy from $\alpha = 0.50$ to $\alpha = 0.10$ with increasing participant multiplicity (decreasing impact parameter).

Overall isotropy of pion production, as required for pions by the thermodynamic model,^{15,16} is thus achieved to within 15% in near-head-on collisions. Predictions of the intranuclear-cascade model³ (INC) are shown in Fig. 1(b). The low-energy pions are isotropic in this model also, but the INC predicts an anisotropy increasing with pion energy, following the trend of the data for the intermediate energies. Within the INC this intermediate region is dominated by pions produced in the corona of the interacting nuclei, where nucleons only undergo one or two collisions. The pions produced in this region therefore reflect the strongly anisotropic angular distributions characteristic of pion production via the Δ resonance in nucleon-nucleon collisions.¹⁴ However, the INC fails to predict the decline in anisotropy at high pion energies.

The thermodynamic model^{15,16} predicts that the c.m. energy spectra will be represented by a temperature T which characterizes a Maxwell-Boltzmann gas:

$$\begin{aligned} d^2\sigma/dE d\Omega &= pE d^3\sigma/dp^3 \\ &= \text{const} \times pE \exp(-E/T), \end{aligned} \quad (3)$$

where p and E are the pion c.m. momentum and total energy, respectively. It is important to note that in this model only $d^3\sigma/dp^3$ should follow a simple

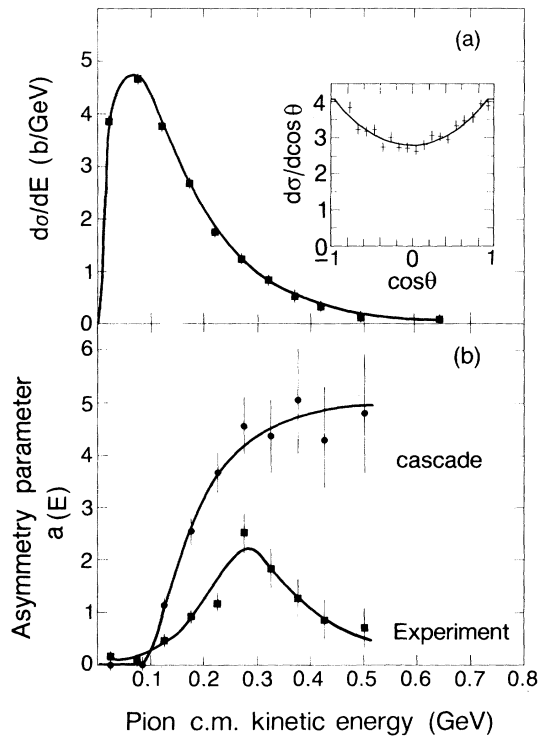


FIG. 1. (Inset) Distribution of pion emission angles $d\sigma/d\cos\theta$ observed for near central collisions of Ar + KCl at 1.8 GeV/nucleon. Only statistical errors are shown in the data, as is done throughout the paper. The curve is a fit using Eq. (2), with arbitrary units. (a) The total yield of pions $\sigma(E)$ integrated over angle as a function of pion c.m. kinetic energy. (b) The anisotropy parameter $a(E)$ plotted as a function of pion c.m. kinetic energy. Squares show the data; circles give the results of an intranuclear-cascade calculation. The lines are drawn to guide the eye.

exponential law whereas $d^2\sigma/d\Omega dE$ and the invariant cross section, $E d^3\sigma/dp^3$, will contain additional energy-dependent factors. The effective temperatures extracted from our data by use of Eq. (3) are not the same as the inverse exponential slope parameters reported in previous investigations^{6,8} which incorrectly fitted $E d^3\sigma/dp^3$ by an exponential law. In order to minimize the effect of the corona, we consider henceforward only the spectra at $\theta_{c.m.} = 90^\circ$. The 90° pion spectrum is shown in Fig. 2(a) together with a fit using Eq. (3) with $T = 69 \pm 3$ MeV. The fit underestimates the data for total pion c.m. energies above 0.5 GeV. A two-temperature fit, with $T_1 = 58 \pm 3$ MeV for $(59 \pm 1)\%$ of the total yield, and $T_2 = 110 \pm 10$ MeV for the remaining $(5 \pm 1)\%$, leads to good agreement. The higher-temperature component is isotropic and is the one that reduces the anisotropy at high pion energies in Fig. 1(b). The corresponding proton spectrum at $\theta_{c.m.} = 90^\circ$ for central collisions is well fitted with a single Boltzmann spectrum with $T_p = 118 \pm 2$ MeV.

The thermodynamic model of Hagedorn and

Rafelski¹⁷ predicts a proton temperature of $T_p = 120$ MeV, close to the observation, but a pion temperature of $T_\pi = 110$ MeV, considerably higher than that observed except for the small 5% component. In this model the difference in predicted temperatures for protons and pions is due to the earlier freezeout of protons, similar to the qualitative argument of Ref. 8. However, the effect is far too small to explain the data. The intranuclear-cascade-model prediction for the pion spectrum is shown in Fig. 2(b). It is closely approximated by a fit with $T_\pi = 73 \pm 3$ MeV. The INC prediction for the proton spectrum is also similar to a Boltzmann distribution, with $T_p = 123 \pm 2$ MeV. The INC is therefore much more successful than the thermodynamic model, in the treatments derived thus far.

In order to understand the vastly different proton and pion temperatures and the successes and failures of the two models it is necessary to consider a thermal system of nucleons and deltas. Insofar as delta formation and decay govern the pion production process, most of the observed pions result from a resonance decay. This two-body decay introduces a distinctly nonthermal aspect into the pion spectra. Thus, although the Δ fraction of the expanding system may well be in thermal equilibrium with the nucleons, the finally established pion spectra have the two-body decay kinematics superimposed on the thermal distribution of the parent Δ states. The resultant pion and proton spectra are quite similar to Boltzmann distributions, but at effective temperatures which are not equal to the temperature of the emitting system of deltas (and nucleons).^{15,18} This parent-daughter mechanism provides a simple relationship¹⁸ between T_p and T_π on the one hand and T_Δ and m_Δ on the other, in which T_p reflects mainly T_Δ while T_π is sensitive to m_Δ . For the observed values $T_p = 118$ MeV and $T_\pi = 58$ MeV we find that $T_\Delta = 135$ MeV and $m_\Delta = 1176$ MeV. The value of T_Δ is plausible in the thermodynamic model but must be taken as an upper limit, since only a fraction of the observed protons originates from Δ decay. The value m_Δ need not equal 1232 MeV, since it is a convolution of the formation cross section and the distribution of relative energies in the $NN \rightarrow N\Delta$ and $\pi N \rightarrow \Delta$ channels. We extracted m_Δ from the INC model by taking the average effective mass of the πN system at the last interaction, and found it to be 1200 MeV.

It is interesting to study next the extent to which our conclusions might be modified by the presence of collective flow, which would also lead to a larger effective temperature for the protons than for the pions.³⁻⁵ This is especially relevant since we have

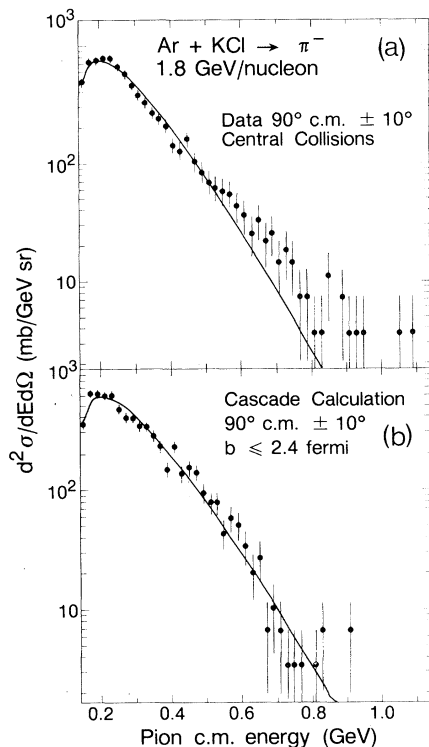


FIG. 2. (a) Pion energy spectrum at 90° in the c.m. system together with a Maxwell-Boltzmann gas-model fit using Eq. (3) with $T_\pi = 69$ MeV. (b) Calculated pion energy spectrum at 90° c.m. for the INC model, together with a fit with $T_\pi = 73$ MeV.

suggested¹ that as much as 35% of all the available energy may be stored in compression at the high-density stage of the collision, to be released later into collective flow, or degraded into thermal energy. The effect of collective flow can be estimated by introduction of a uniform radial velocity distribution for the Δ 's. This requires folding a function into the Δ temperature distribution identical in form to that which we use to calculate the parent-daughter effect. The inevitable result is a Boltzmann-type spectrum with an effective temperature. Whether the pions and protons emerge from a Δ spectrum with a true temperature or an effective temperature the result is very similar. We have attempted to fit the proton spectrum with various combinations of true Δ temperatures and radial flow velocities. We find that even in an idealized situation with improved statistics it is difficult to distinguish the result from a true Boltzmann distribution. Only when the flow velocity was increased above $\beta=0.4$ could a distinction be observed. The resolution of this question remains as a major challenge for both theory and experiment.

In conclusion, for central collisions of Ar+KCl at 1.8 GeV/nucleon the bulk of the pions are produced isotropically in the c.m. frame. There is an anisotropic forward-backward peaked component for pion kinetic energies of 200 to 350 MeV, probably due to pions produced in the corona of the interacting region, where nucleons collide only once or twice. The 90° c.m. pion spectrum can be fitted by a two-temperature classical thermal distribution with 95% at $T_1=58$ MeV and a second 5% component with $T_2=110$ MeV apparent at pion total energies above 500 MeV. The 90° c.m. proton spectrum showed only one component, with $T=118$ MeV. The primary difference in the pion and proton temperatures can be reconciled by considering an equilibrated N, Δ system at thermal freezeout and taking into account the kinematics of Δ decay. In this model the proton temperature more closely reflects the freezeout temperature while the pion temperature is mainly given by the Δ mass distribution at freezeout. The effective delta

mass at thermal freezeout is found to be considerably lighter than 1232 MeV. Finally, a 5% high-temperature pion component is observed; it may be a result of thermally equilibrated pions or higher resonances not treated in the cascade model.

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¹R. Stock *et al.*, Phys. Rev. Lett. **49**, 1239 (1982).

²J. W. Harris *et al.*, Lawrence Berkeley Laboratory Report No. LBL-17404 (to be published).

³P. Siemens and J. Rasmussen, Phys. Rev. Lett. **42**, 880 (1979).

⁴H. Stocker, A. A. Ogloblin, and W. Greiner, Z. Phys. A **303**, 259 (1981).

⁵H. W. Barz *et al.*, Z. Phys. A **302**, 73 (1981).

⁶S. Nagamiya *et al.*, Phys. Rev. C **24**, 971 (1981).

⁷S. I. A. Garpman *et al.*, Phys. Lett. **86B**, 3 (1979).

⁸S. Nagamiya, Phys. Rev. Lett. **49**, 1383 (1982).

⁹J. Cugnon, D. Kinet, and J. Vandermeulen, Nucl. Phys. A **379**, 553 (1982).

¹⁰J. Cugnon, T. Mizutani, and J. Vandermeulen, Nucl. Phys. A **352**, 505 (1981).

¹¹A. Sandoval *et al.*, Phys. Rev. Lett. **45**, 874 (1980).

¹²H. Ströbele *et al.*, Phys. Rev. C **27**, 1349 (1983).

¹³A. Sandoval *et al.*, Nucl. Phys. A **400**, 365c (1983).

¹⁴R. Allen *et al.*, Lehigh University Report No. LEH-HEP 79-4-1, 1979 (unpublished).

¹⁵R. Hagedorn and J. Ranft, Suppl. Nuovo Cimento **6**, 169 (1968).

¹⁶J. Gosset *et al.*, Phys. Rev. C **16**, 629 (1977).

¹⁷R. Hagedorn and J. Rafelski, Phys. Lett. **97B**, 136 (1980).

¹⁸R. Hagedorn, CERN Report No. TH 3684, 1984 (to be published).