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Abstract

Pion and proton production are measured to investigate thermal equilibrium in central collisions of ^{40}Ar + KCl at 1.8 GeV/nucleon. The bulk of the pion yield is found to be isotropic in the c.m., 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 kinematics of the decay of delta resonances in thermal equilibrium. A 5 ± 1% isotropic component in the pion spectrum is, however, found to have a temperature of 110 ± 10 MeV, near to that of the protons and Δ's.

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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.[3,4,5] Previous experimental studies of the pion spectra have been for inclusive measurements only.[6] Attempts have been made to fit the results using a variety of hypotheses, including collective flow,[3,4,5] 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-like temperature distributions, but with very different effective temperatures. We find that the results can most simply be described using 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 LBL Streamer Chamber facility was used to study central collisions of Ar + 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 Reference 13. Events were selected to correspond to impact parameters of less than 2.4 fm. It has been found by exclusive measurements of the protons [12] 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

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

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

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

The insert in Fig. 1a shows the distribution $d\sigma/d\cos\theta$ and a fit with eq. (2) where $a = 0.52$. As the ratio of the anisotropic fraction to the total yield is given by $\alpha = \frac{a}{a+3}$ in this parameterization, a mean anisotropy of $\alpha = 0.15$ is found. This fairly low degree of anisotropy 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 Fig. 1a and 1b, respectively. Staying near zero for $E \leq 100$ MeV, a(E) rises to a peak at $E \simeq 300$ MeV where $\alpha = 0.45$, then falls again to $\alpha < 0.20$ at

$E > 400$ MeV. Fig. 1a 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 results[6] have been reported for 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 fall-off 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 model[3] (INC) are shown in Fig. 1b. 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 anistropy 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:

$$d^2\sigma/dEd\Omega = p \cdot E \cdot d^3\sigma/dp^3 = \text{const.} \cdot p \cdot E \cdot \exp[-E/T] \qquad (3)$$

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 exponential law whereas $d^2\sigma/d\Omega dE$ and the invariant cross section, $E \cdot d^3\sigma/dp^3$, will contain additional energy-dependent factors. The effective temperatures extracted from our data by using eq. (3) are not the same as the inverse exponential slope parameters reported in previous investigations[6,8] which incorrectly fitted $E \cdot d^3\sigma/dp^3$ to an exponential law. In order to minimize the effect of the corona, we consider henceforward only the spectra at $\theta_{CM} = 90°$. The 90° pion spectrum is shown in Fig. 2a together with a fit using eq. (3) with T = 69 ± 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 95 ± 1% of the total yield, and $T_2 = 110 \pm 10$ MeV for the remaining 5 ± 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. 1b. The corresponding proton spectrum at $\theta_{cm} = 90°$ for central collisions is well fitted with a single Boltzmann spectrum with $T_p = 118 \pm 2$ MeV.

The thermodynamic model of Hagedorn and Rafelski[17] 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 Reference 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. 2b. 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, at this stage of the discussion.

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 governs the pion production process, most of the observed pions result from a resonance decay. This two body decay introduces a distinctly non-thermal 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 relationship between T_p and T_π on the one hand and T_Δ and m_Δ on the other. Fig. 3 shows the proton and pion "temperatures" (a) as a function of T_Δ for $m_\Delta = 1232$ MeV and (b) as a function of m_Δ for $T_\Delta = 135$ MeV. One sees that 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, while the effective Δ mass 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 this from the INC model by taking the average effective mass of the πN system at the last interaction: the value obtained is 1200 MeV. The above discussion is not entirely exact: whereas the bulk of the pion cross section is expected to result from Δ decay, this is not so for the protons. From the observed pion to proton participant multiplicity ratio of 0.3 at this energy,[11] not all of the total proton yield results from Δ decay. Thus the observed T_p only approximately represents the temperature of the Δ decay proton fraction.

The nearly quantitative success of this simple analysis explains why the INC is successful in explaining the large difference between the pion and proton spectra: it correctly includes the Δ-decay kinematics. The thermodynamic model may be equally successful if the Δ-decay kinematics is introduced.

It is interesting to study next to what extent our conclusions might be modified by the presence of collective flow, which would increase the effective temperature of the protons more than that of the pions.[3,4,5] This is specially relevant since we have previously suggested[1] that as much as 35% of all the available energy may be stored in compression effects at the high density stage of the collision, to be released again into collective flow in the final stage, or else degraded into thermal energy. The effect of collective flow can be estimated by introducing 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 previously used to calculate the parent-daughter effect. The inevitable result is a Boltzmann-like 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. When the flow velocity was increased above $\beta = 0.4$ a distinction could be observed. However, this limit is too large to be interesting. 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 spectra 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 freeze-out and taking into account the kinematics of Δ decay. In this model the proton temperature more closely reflects the freeze-out temperature while the pion temperature is mainly given by the Δ mass distribution at freeze-out. The effective delta mass at thermal freeze-out 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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Figure Captions

1. (a insert) 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. Curve is a fit using eq. (2), 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 results of an intranuclear cascade calculation. The lines are drawn to guide the eye.

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.

3. (a) Dependence of pion and proton temperatures T_π and T_p on Δ temperatures T_Δ for $m_\Delta = 1232$ MeV.

   (b) Dependence of T_π and T_p on m_Δ for $T_\Delta = 135$ MeV.

References

1. R. Stock et al., Phys. Rev. Lett. 49 (1982) 1236
2. J. W. Harris et al., LBL-17404, to be published
3. P. Siemens and J. Rasmussen, Phys. Rev. Lett. 42 (1979) 880
4. H. Stocker, A. A. Ogloblin and W. Greiner, Z. Phys. A303 (1981) 259
5. H. W. Barz et al., Z. Phys. A302 (1981) 73
6. S. Nagamiya et al., Phys. Rev. C24 (1981) 971
7. S. I. A. Garpman et al., Phys. Lett. 86B (1979) 3
8. S. Nagamiya, Phys. Rev. Lett. 49 (1982) 1383
9. J. Cugnon, D. Kinet and J. Vandermeulen, Nucl. Phys. A379 (1982) 553
10. J. Cugnon, T. Mitzutani and J. Vandermeulen, Nucl. Phys. A352 (1981) 505
11. A. Sandoval et al., Phys. Rev. Lett. 45 (1980) 874
12. H. Stroebele et al., Phys. Rev. C27 (1983) 1349
13. A. Sandoval et al., Nucl. Phys. A400 (1983) 365c
14. R. Allen et al., Lehigh report LEH-HEP 79-4-1, 1979, unpublished
15. R. Hagedorn und J. Ranft, Suppl. Nuovo Cimento 6 (1968) 169
16. J. Gosset et al., Phys. Rev. C16 (1977) 629
17. R. Hagedorn and J. Rafelski, Phys. Lett. 97B (1980) 136
18. R. Hagedorn, CERN preprint TH 3684, 1984

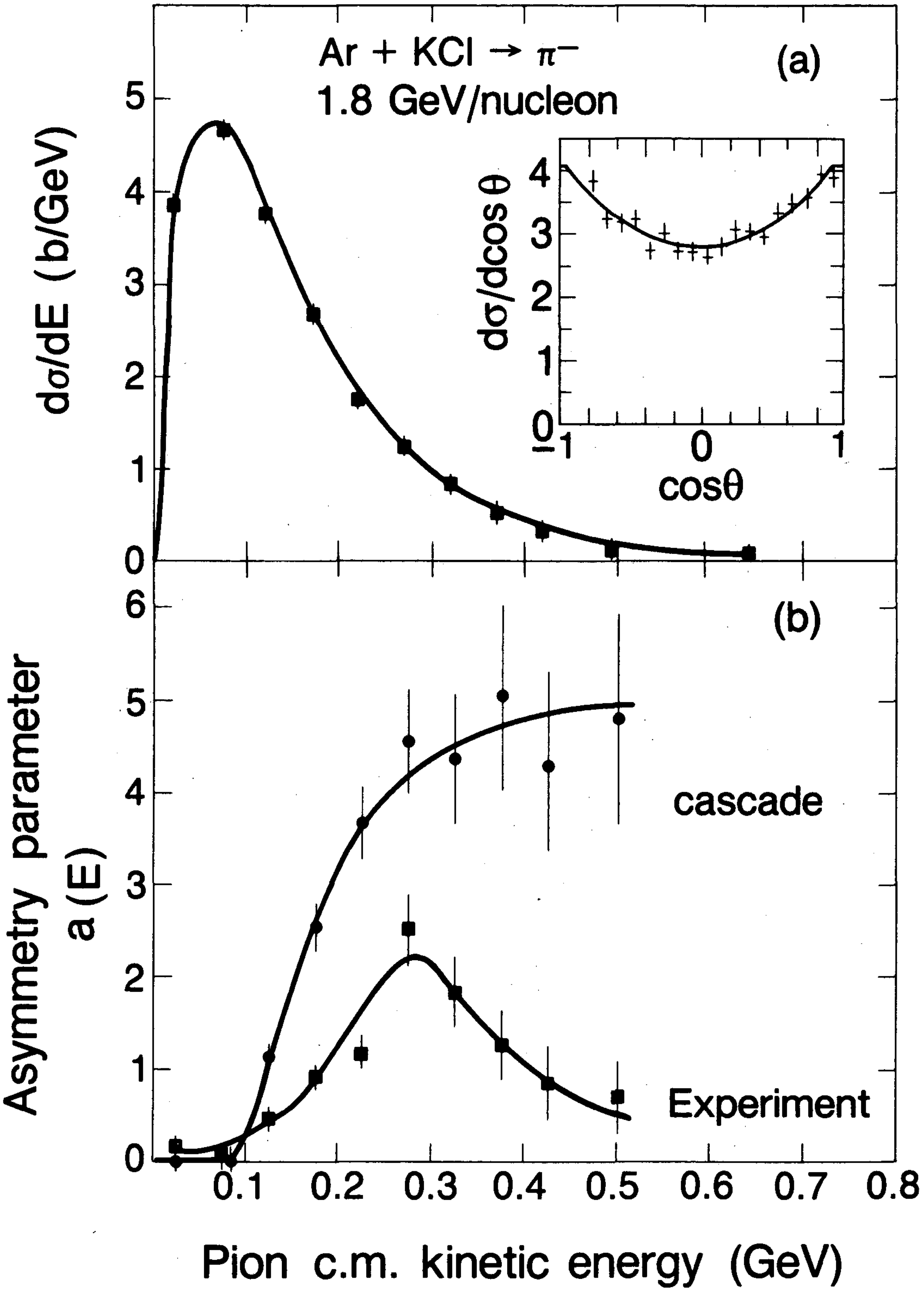

FIG. 1

XBL 844-10393

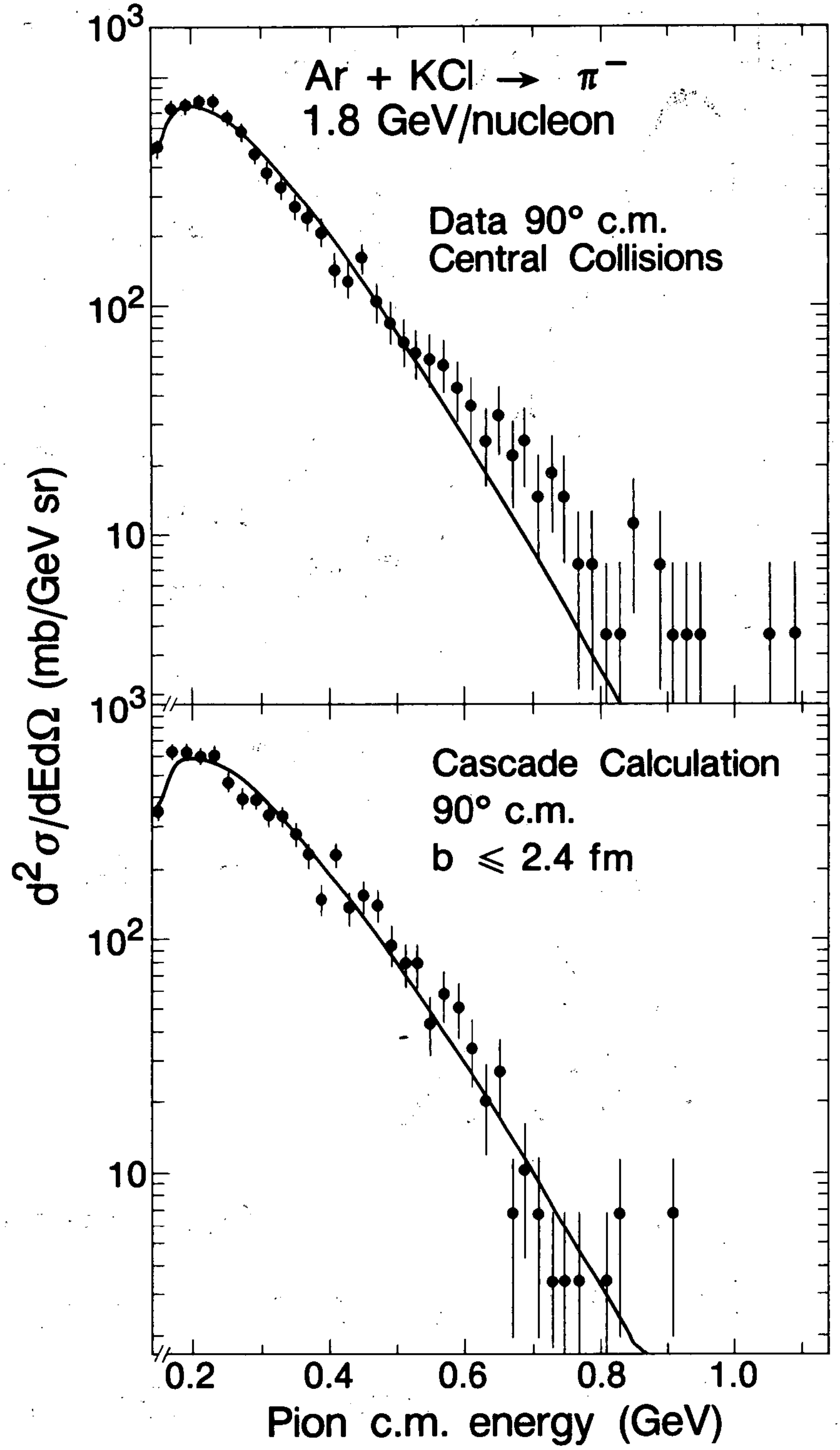
Ar + KCl → π^-
1.8 GeV/nucleon
Data 90° c.m.
Central Collisions
Cascade Calculation
90° c.m.
b ⩽ 2.4 fm
10^3
10^2
10
10^3
10^2
10
$d^2\sigma/dEd\Omega$ (mb/GeV sr)
0.2
0.4
0.6
0.8
1.0
Pion c.m. energy (GeV)
XBL 845-9376

FIG. 2

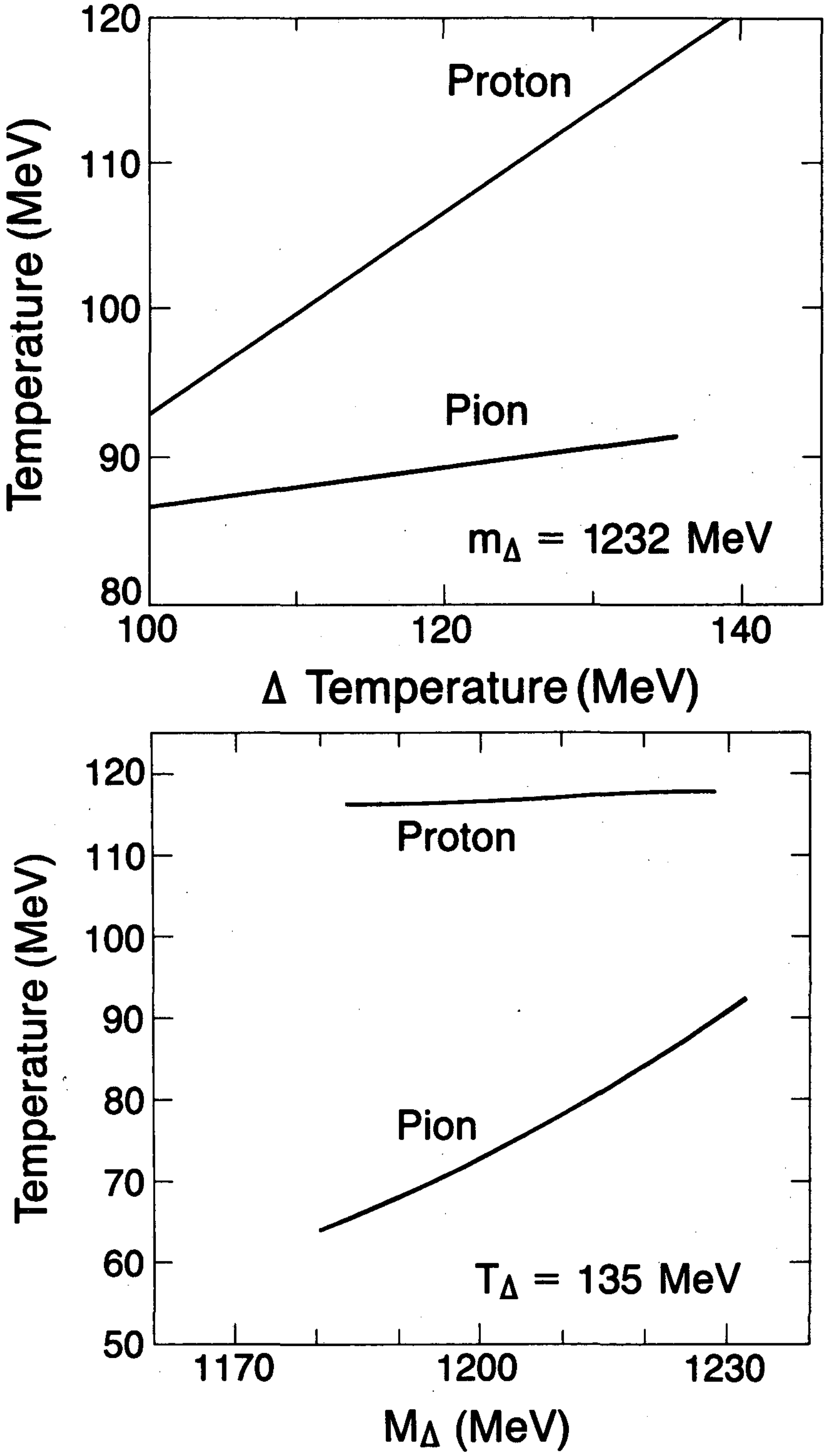
Temperature (MeV)
120
110
100
90
80
Proton
Pion
m_Δ = 1232 MeV
100
120
140
Δ Temperature (MeV)
Temperature (MeV)
120
110
100
90
80
70
60
50
Proton
Pion
T_Δ = 135 MeV
1170
1200
1230
M_Δ (MeV)
XBL 844-10396A

FIG. 3

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