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PION PRODUCTION IN THE $^{40}Ar + ^{40}Ca$ REACTION AT 1.05 GeV/Nucleon

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ABSTRACT

Pion production cross sections have been measured for the $^{40}Ar + ^{40}Ca \rightarrow \pi^+ + X$ reaction at a laboratory energy of 1.05 GeV/nucleon. A maximum in the π^+ cross section occurs at mid-rapidity, which is anomalous relative to p + p and p + nucleus reactions and compared to many other heavy ion reactions. Calculations based on cascade and thermal models fail to fit the data.

In high-energy heavy-ion reactions it is generally believed that single particle inclusive cross sections of π, p, d, t, etc. are dominated by simple factors such as geometry and energy-momentum conservation, and contain little information about the initial "compression" or early "expansion" stages of central or near-central collisions.[1] This may be attributed to the effect of averaging caused by large particle multiplicities, the acceptance of events from all impact parameters, and the rescattering of products due to very short mean free paths. For similar reasons, theoretical models using cascade,[2,3] firestreak[4] or hydrodynamic[5] assumptions usually give semi-quantitative agreement with particle-inclusive data.[6] Therefore, it is interesting that in the present study of the $^{40}Ar + {}^{40}Ca$ reaction at 1.05 GeV/nucleon, the π^+ emission pattern is peaked in the mid-rapidity region, which is not predicted by theoretical calculations and is unique compared to p+p and p + nucleus reactions and heavy-ion reactions at lower bombarding energies. Because of this unusual behavior, the possibility must be considered that the structure in the π^+ cross section near 90° in the center of mass may be a signature of processes from an early stage of the reaction which has not been fully averaged out.

One can understand how such inforamtion might survive in this particular instance for low-energy pions produced in a rather light system. Because of a large energy threshold, pions are produced preferentially in regions of high density and temperature or from particularly violent nucleon-nucleon collisions, with little contribution from spectator deexcitation. Furthermore, since these pion energies near 90°

in the center of mass are well below the $\Delta(1232)$ resonance energy, it is expected that the mean free path is comparable to the dimensions of the $^{40}Ar + ^{40}Ca$ system, allowing an appreciable amount of unattenuated pion emission.

A beam of ^{40}Ar ions at 1.05 GeV/nucleon from the Lawrence Berkeley Laboratory Bevalac was used to induce reactions in a 200 mg/cm^2 Ca target. Pions were identified and the energy spectra were measured over a range of 15-95 MeV with a multi-element dE/dx telescope[1] consisting of a 5 mm Si(Li) crystal, and 28 mm and 42 mm intrinsic germanium crystals with a Si(Li) reject counter. A delayed coincidence technique was applied to identify stopped π^+ by observing the positrons from the subsequent muon decay in the germanium crystals of the detector, from the decay sequence $\pi^+ \xrightarrow{25\ \mathrm{ns}} \mu^+ + \nu$ and $\mu^+ \xrightarrow{2.2\ \mu\mathrm{s}} e^+ + \nu + \bar{\nu}$. Pion energy spectra were corrected for absorption, multiple scattering, and for the inefficiency of detecting the positrons produced in the muon decay. The systematic uncertainty in the π^+ cross sections is estimated to be ≈30% with a precision better than 10%. In addition to the pion inclusive measurements, the associated charged-particle multiplicity was determined on an event-by-event basis, allowing a type of impact parameter selection.[1] The multiplicity was measured with an 80-counter array of plastic scintillators coupled to photomultiplier tubes and discriminators. The array covered 67% of the forward hemisphere and was sensitive to p, d, t, etc. with energies greater than ≈25 MeV/nucleon and charged pions with energies greater than 10 MeV.

The measured π^+ energy spectra are shown in Fig. 1 along with the results of an intranuclear cascade calculation, using the code of Fraenkel and

Yariv,[3] and the predictions of the firestreak model of Gosset, Kapusta and Westfall.[4] These two models represent very different assumptions about the reaction. The cascade calculation approaches the problem as one of simple nucleon-nucleon collisions, using a pure isobar model for pion production and absorption. In the nuclear firestreak model it is assumed that in the overlapping region of the target and projectile nucleons, thermodynamic and chemical equilibria are established among the hadrons, with an isoergic expansion to the freeze-out density, here assumed to be 0.12 hadrons/fm^3. It can be seen in Fig. 1 that neither model gives a satisfactory fit to the data, differing by factors of $\approx$2-3 at the extreme ends of the measured spectra. This cannot be considered reasonable agreement if we are to take these models seriously.

The anomalous nature of the pion emission in the ^{40}Ar + ^{40}Ca reaction is perhaps better demonstrated in Fig. 2a by comparison with other experimental data and by transforming the data to a "rapidity plot" which is generally useful in obtaining qualitative information about emission sources of particles. The most prominent feature of Fig. 2a is the enhanced pion yield at mid-rapidity, i.e. at the center of mass of the target-projectile system, and at a perpendicular momentum of $\approx 0.4\ m_{\pi}$ ($\approx$55 MeV/c). The only other target-projectile combination studied to date which exhibits similar structure in the pion spectra is the reaction[7] of 800 MeV/nucleon ^{20}Ne + NaF. This structure is not seen at lower energies, such as in the 400 MeV/nucleon ^{20}Ne + ^{27}Al reaction,[8] but it is not known whether this is a real change in the phenomenon, or if the small separation between target and projectile rapidities masks the effect.

A cross section pattern like that shown in Fig. 2a is quite unexpected. In a fireball model, pion emission is isotropic in the CM system of an equal mass collision with an exponentially decaying energy spectrum,[4] creating nearly semi-circular contours centered at mid-rapidity and at $p_\perp = 0$. For a nucleon-nucleon collision picture, we may use the cascade calculation of Fig. 1 for $^{40}Ar + {}^{40}Ca$, which gives qualitatively the same results as for the pion-inclusive data of Cochran et al[9] for the p + p reaction at a slightly lower beam rapidity, plotted in Fig. 2b. The p + p data can be understood in terms of the decay of an isobar nearly at rest in the center of mass. The characteristic forward-backward peaking with a pion momentum of ≈230 MeV/c, shows little similarity to the $^{40}Ar + {}^{40}Ca$ data. In particular, the p+p reaction has a very small pion yield at mid-rapidity (90° CM) and at $p_\perp \approx 0.4\ m_\pi$. Similarly, only small pion yields are observed in this region for p + nucleus reactions,[8,9] which may be expected to show effects associated with the Fermi motion, and with pion absorption and scattering. But reactions of unequal target and projectile masses do not have a unique center of mass of the participants, making interpretation difficult. It is unlikely that pion attenuation is important for the $^{40}Ar + {}^{40}Ca$ reaction, due to a long mean free path expected in the energy range of interest here.[10] Also, we investigated the effect of gating on high charged-particle multiplicities in order to select more central collisions.[1] If attenuation effects were important in the participant or spectator regions the change in shadowing geometry accompanying this impact parameter restriction should alter the emission pattern, as seems to be the case for ^{20}Ne- and ^{40}Ar-induced reactions on heavy targets.[8] Instead, as shown by the spectra in Fig. 3, no significant change is observed here, for a restriction of the impact parameter to less than an estimated 4 fm, compared to a grazing distance of 8 fm. This seems to hold for the spectral shapes and angular distributions, both in the mid-rapidity region near 90° at $p \approx 50$ MeV/c and at $p \approx 200$ MeV/c where isobar decay should contribute.

The lack of an impact parameter dependence of the spectral shapes is expected in a fireball model for an equal mass target-projectile reaction because all impact parameters result in the same forward momentum and temperature for the participants. However, sideways peaked CM angular distribution cannot be explained, which is an especially significant shortcoming of the thermal models for low energy pions with small shadowing effects. Also the measured energy spectra fall off much more rapidly at high energy than is predicted. Qualitatively the energy spectra can be accounted for by lowering the temperature of the emitting fireball, for instance, by early emission of pions or by adding a compression energy term to the fireball model.[11,12] The angular distribution is more difficult to explain and hints strongly at collective, hydrodynamic flow effects[13] to account for the preferential sideways ejection of pions observed here.

Coulomb repulsion in the π^+-nucleus system may be partially responsible for the broad maxima in the 75° and 90° spectra of Fig. 3, but cannot account for the rapid fall-off at high momentum, and for the fact that the corresponding cross section maximum occurs at a slightly <u>higher</u> momentum in the lighter ^{20}Ne + NaF system.[7]

In summary, π^+-inclusive data for the $^{40}Ar + ^{40}Ca$ reaction at 1.05 GeV/nucleon are found to have some striking features compared to other target-projectile combinations. A rapidity plot of the data shows an enhanced pion yield centered at mid-rapidity, forming a unique pattern which is insensitive to multiplicity selection. Poor fits to the data indicate that this effect is not accounted for in the thermal and cascade models.

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Footnotes and References

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Figure Captions

Fig. 1. Pion-inclusive double differential cross sections in the laboratory system for the $^{40}Ar + ^{40}Ca \rightarrow \pi^+ + X$ reaction at 1.05 GeV/nucleon. Statistical errors are smaller than the size of the points except where indicated. The histograms (solid lines) show the results of a nuclear cascade calculation[3] and the dashed lines represent a nuclear firestreak calculation.[4]

Fig. 2. Constant contours of Lorentz invariant pion cross section, $(1/p)\ d^2\sigma/(d\Omega dE)$, in units of $b/(sr \cdot GeV^2/c)$ as a function of perpendicular pion momentum and rapidity, y. Part (a) shows the results of the present study for 1.05 GeV/nucleon ^{40}Ar + ^{40}Ca, and part (b) was constructed from data for the p + p reaction[9] at 730 MeV. Both sets of data have been reflected through mid-rapidity, $(y_p + y_T)/2$, shown by the dashed vertical lines. The areas within the maximum contours have horizontal shading. The shaded edges indicate the limits of the experimental measurements.

Fig. 3. Invariant cross section as a function of momentum for the center-of-mass angles 30, 45, 60, 75 and 90 degrees. Part (a) represents π^+ inclusive cross sections. In part (b) the detected π^+ were coincidence gated by the requirement that at least 20 charged particles were detected in the multiplicity array, corresponding to the upper 15% of the multiplicity distribution.

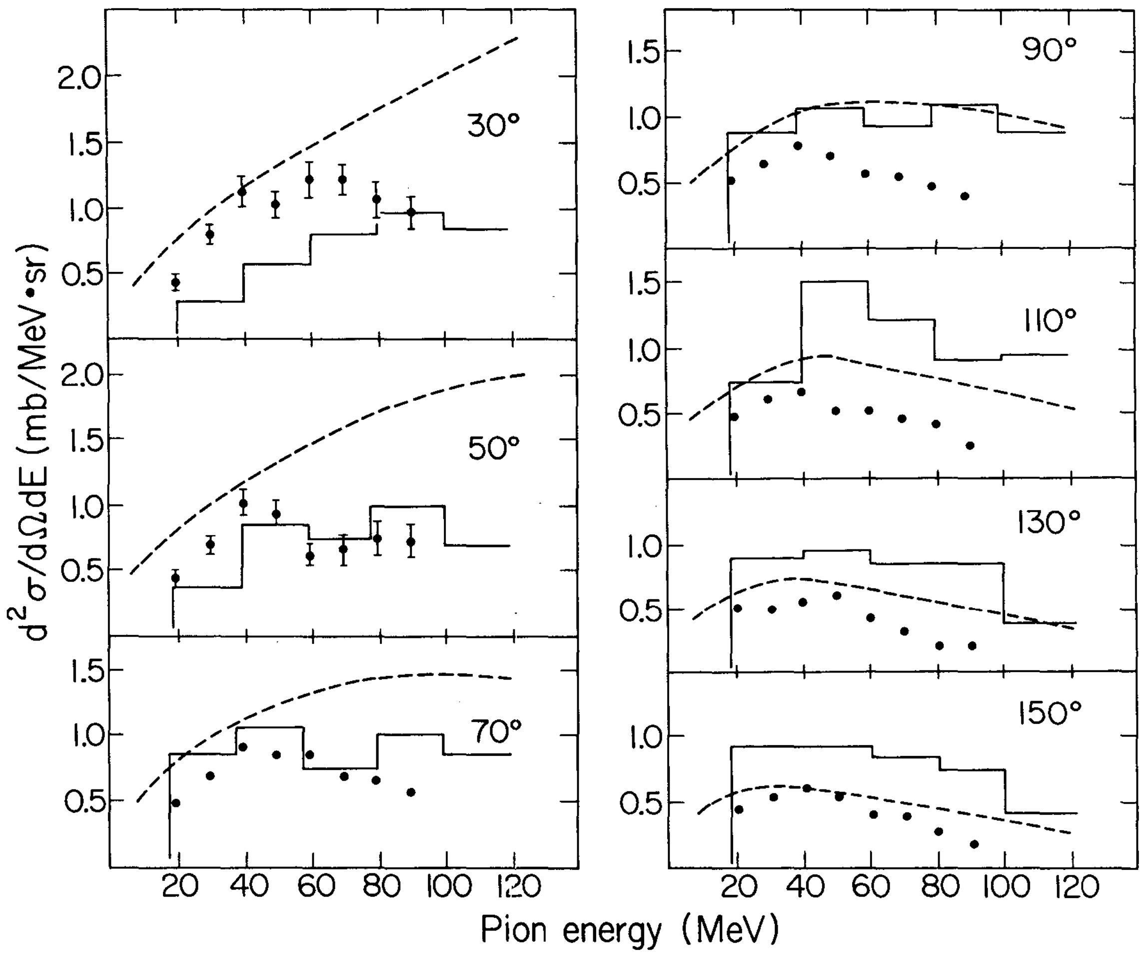

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Fig. 1

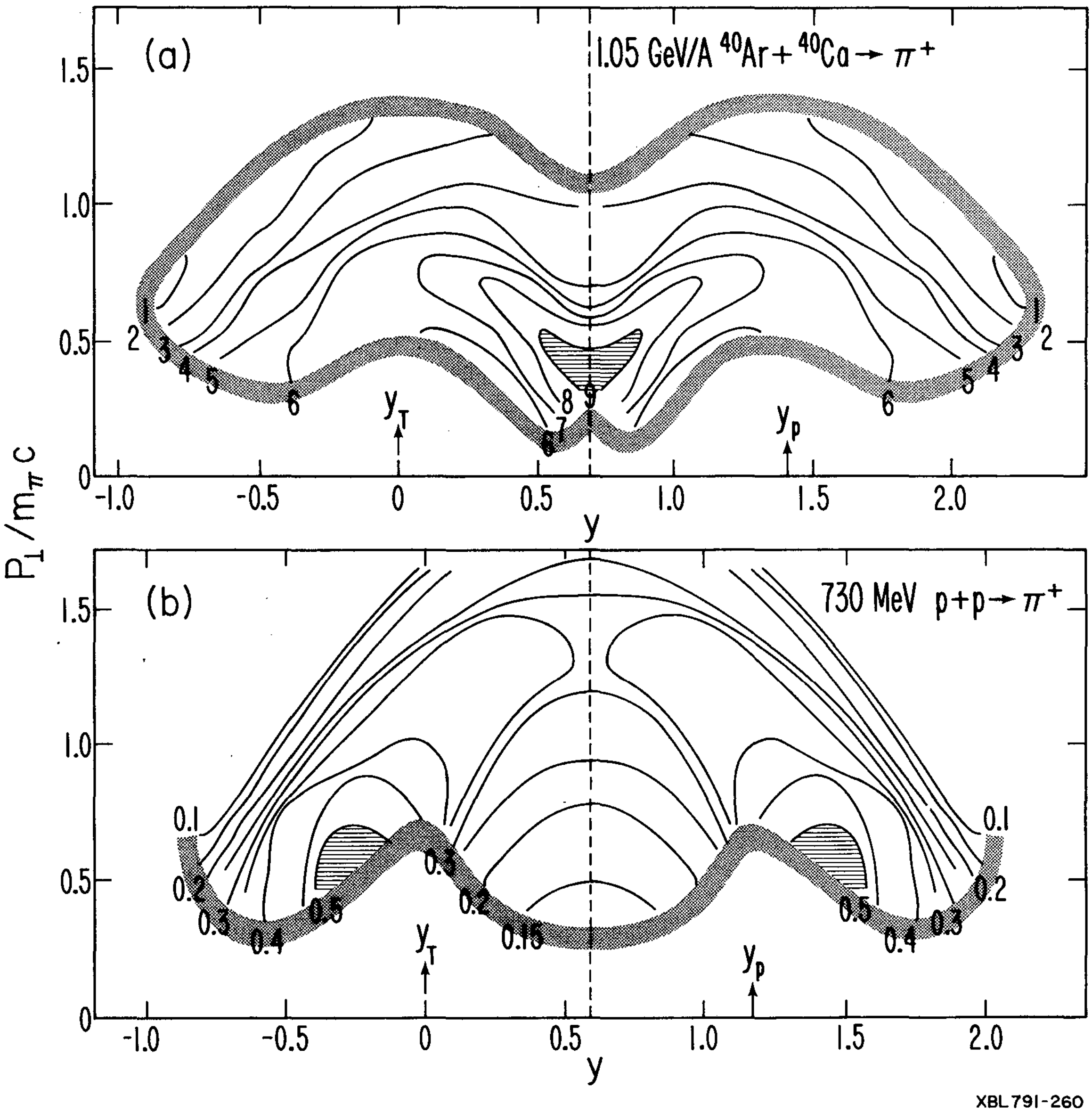
(a)
1.05 GeV/A ^{40}Ar + ^{40}Ca → π^+
(b)
730 MeV p + p → π^+
$P_\perp / m_\pi c$
y
y_T
y_p
0.1
0.2
0.3
0.4
0.5
0.15
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Fig. 2

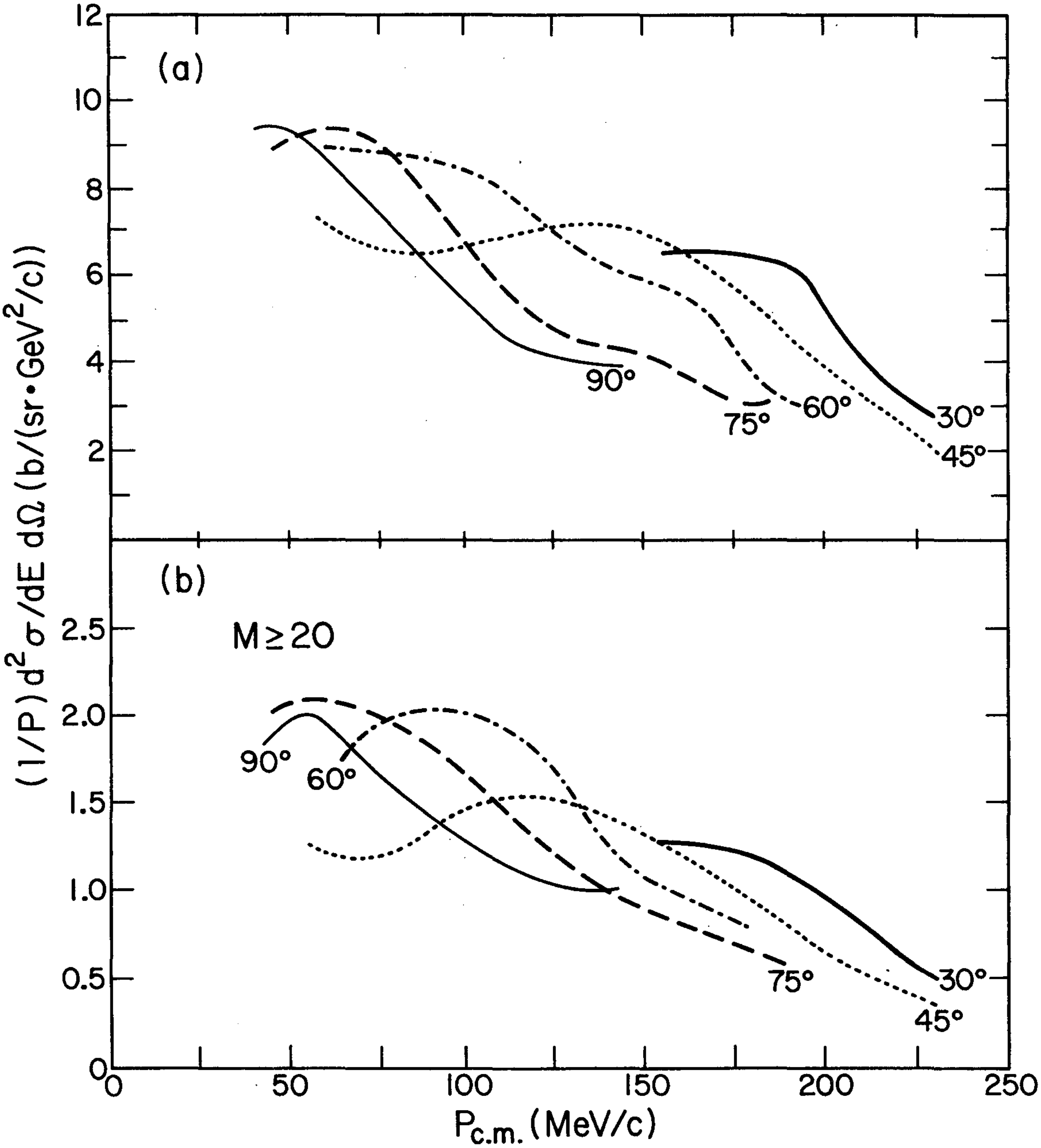
(a)
(b)
M≥20
(1/P) d²σ/dE dΩ (b/(sr•GeV²/c))
P c.m. (MeV/c)
90°
75°
60°
30°
45°
0
50
100
150
200
250
12
10
8
6
4
2
2.5
2.0
1.5
1.0
0.5
0
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Fig. 3

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