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Pions produced near the center-of-mass velocity in heavy-ion collisions

K. A. Frankel, J. A. Bistirlich, R. Bossingham, H. R. Bowman, K. M. Crowe,
C. J. Martoff,* D. Murphy, J. O. Rasmussen, J. P. Sullivan, W. A. Zajc
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

J. P. Miller
Department of Physics, Boston University, Boston, Massachusetts 02215

O. Hashimoto and M. Koike
Institute for Nuclear Study, Tokyo, Japan and Lawrence Berkeley Laboratory, Berkeley, California 94720

J. Peter
Institut de Physique Nucléaire, Orsay, France

W. Benenson, G. M. Crawley, E. Kashy, and J. A. Nolen, Jr.
Michigan State University, East Lansing, Michigan 48824

J. Quebert
Université de Bordeaux, Le Haut-Vigneau, 33170 Gradignan, France
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The cross section for producing π^+ and π^- at velocities close to that of the center of mass was studied for the ^{40}Ar + ^{40}Ca reaction at $E/A = 1.05$ GeV. The π^+ and π^- data show a flat plateau around $y_{\rm c.m.}=0$. The π^-/π^+ ratio of 1.5 ± 0.2 is much lower than published theoretical predictions. Data were also obtained for carbon and uranium targets.

[NUCLEAR REACTIONS C(^{40}Ar,$\pi^\pm$), Ca(^{40}Ar,$\pi^\pm$), U(^{40}Ar,$\pi^\pm$); $E/A = 1050$ MeV; measured $\sigma(E,\theta)$.]

In relativistic heavy-ion collisions it has proven difficult to find convincing signatures of a central fireball in which the initial longitudinal momenta of participant nucleons have been completely degraded. In a recent experiment by Wolf *et al.*[1] a difference between pion production by nucleus-nucleus collisions and production by nucleon-nucleon collisions was noted. The contour plots for the cross section of $E/A = 1.05$ GeV ^{40}Ar on ^{40}Ca showed a ridge near $P_\perp = 0.5\ m_\pi c$ and $P_\parallel^{\rm c.m.}=0$ (the "mid-rapidity" region at which the rapidity of the pions is about halfway between that of projectile and target). This enhancement of the cross section is not present in p-p data at 730 MeV (Ref. 2) and was attributed to possible "hydrodynamic flow effects" in the heavy-ion reaction. A similar but less localized enhancement was observed by Chiba *et al.*[3] for $E/A = 800$ MeV Ne on NaF.

One explanation for the effect grew out of a 0° experiment performed at lower energies by Benenson *et al.*[4] In this experiment very strong Coulomb effects were observed by measuring π^-/π^+ ratios for pions moving with velocity small relative to the projectile fragment. Theories by Libbrecht and Koonin[5] and by Gyulassy and Kauffmann[6] were able to explain the general features of the data of Benenson *et al.*[4] and in addition raised the question of whether the π^+ ridge of Wolf *et al.*[1] was caused by the Coulomb fields of the charge strung out between the projectile and target in velocity space. The Coulomb effect observed by Benenson *et al.* was interpreted as being dominated by the field of a "cold" charged beam fragment near 0°, but in the case of Wolf *et al.*[1] the pions are near 90° c.m. and they would feel a reduced effect of target and projectile but an enhanced effect of the hot nuclear matter which has been postulated to exist in the $P_\parallel^{\rm c.m.}=0$ frame [7]. The present experiment was undertaken to measure the differential cross sections for both π^+ and π^- in the center-of-mass region extending from $P_\perp=0$ through the ridge observed by Wolf *et al.*[1]. Measurements of both pion charges should enable Coulomb effects to be distinguished from other effects.

The experiment of Wolf *et al.*[1] covered a wide range of pion energies and angles (30° and greater) and was performed with a solid-state detector telescope. Since the decay $\mu^+ \rightarrow e^+$ was used to identify pions, only positive pions were measured. In the present experiment a magnetic spectrometer with a 30° angular range was set at 15° with respect to the beam. The target was 2.0 g/cm^2 of Ca, giving an overall energy resolution of about 2 MeV. A description of the spectrometer and the detection techniques can be found in a recently submitted publication.[8] Associated multiplicities were not measured in this experiment. Wolf *et al.*[1] claim that there is no significant change in the peak when high multiplicity events ($M \geq 20$) are selected. The spectrometer covered the mid-rapidity range quite well out to $P_\perp \sim 0.6\ m_\pi c$. A comparison in the right half of Fig. 1 with the data of Wolf *et al.*[1] for π^+ at 30° gives good agreement, except for the cases in which the present data were reflected about $P_\parallel^{\text{c.m.}}=0$. The data points given by closed diamonds in Fig. 1 are calculated under the assumption of symmetry of the invariant cross section about the $P_\parallel^{\text{c.m.}}=0$ axis and were taken at the angles and energies given in the caption.

Although only 1–2 standard deviations in disagreement with our data, their lowest energy point at 30° (lab) indicates a rising cross section in contrast to our flat data. This point and their lowest energy point at 50° largely establish the sharp drop on the low $P_\perp$ side of the ridge in their contour plot. In the left half of Fig. 1 we compare our direct data at $y=0.85$ with a cut through their contour plot at the same rapidity. Our data do not show the rise given in their contour plot from $P_\perp=(0.2 \text{ to } 0.6)m_\pi c$ at $y=0.85$.

In this case the plotted points are taken directly from the present data, but the curve is from their contour plot, which includes reflections of data about $P_\parallel^{\text{c.m.}}=0$. It is to be noted that ^{40}Ar + ^{40}Ca is only approximately a symmetric system, so caution is in order regarding reflection of data points through the center of mass.

Can the disagreement arise from differences in experimental resolution? Whatever the ultimate resolution of their solid-state detector telescope, their data are binned in 10-MeV kinetic energy intervals and are separated by 20° in lab angle, coarser than the resolution and binning of the present experiment. The rms resolution for the present experiment is $\langle \Delta y^2 \rangle^{1/2}=0.02\text{–}0.03$ and $\langle \Delta p^2 \rangle^{1/2}=(0.05\text{–}0.06)m_\pi c$ over the range of the spectrometer's acceptance, which is sufficient to observe the peak at 90° c.m. reported by Wolf *et al.*[1]

In order to display most comprehensively the combined data of the two experiments we show contour plots in Fig. 2. The top half of the figure contains all data of both experiments, and the lower half contains only data of Wolf *et al.*[1] The contour maps were drawn by a computer routine, in which all data points and their reflections were equally weighted. The contour maps were modified only by dotting in the location of their actual data points, outlining the region of our 64 data points, and eliminating contours which had been extrapolated into regions of no data, real or reflected. With addition of our data the mid-rapidity region is seen to have a broad plateau around 8 μb sr^{-1} MeV$^{2.}$ This plateau, of width nearly a full unit in rapidity, extends out along 90° c.m. to $P_\perp/m_\pi c$

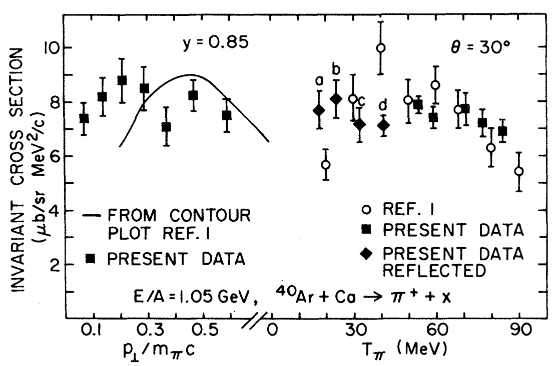

FIG. 1. Comparison of the data of Wolf *et al.* (Ref. 1) with the present results. In the right side of the figure the diamonds are reflections of the present data about the $P=0$ axis. The data were taken: (a) 12°, 77 MeV; (b) 16°, 71 MeV; (c) 20°, 65 MeV; and (d) 24°, 59 MeV. In the left side of the figure, the present data at $y=0.85$ are compared to a cut through the contour plot of Wolf *et al.* On the right side, T_π is the laboratory pion kinetic energy.

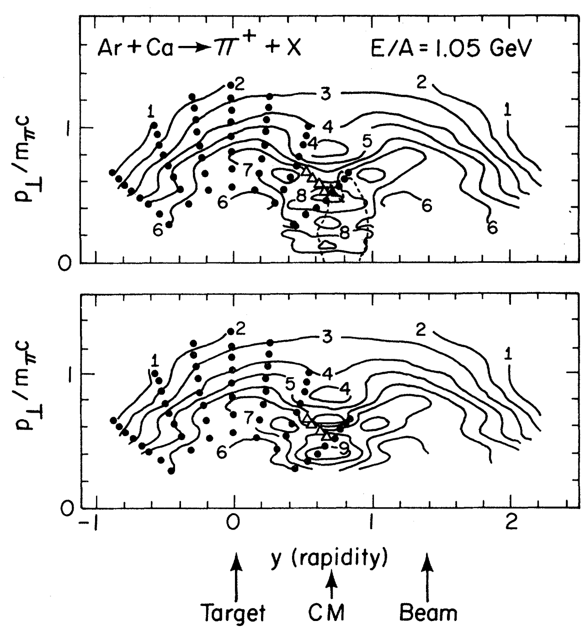

FIG. 2. Computer-drawn contour plots of π^+ Lorentz-invariant cross sections of the ^{40}Ar + ^{40}Ca system at $E/A=1.05$ GeV/N. Closed circles show the locations of data points of Wolf *et al.* (Ref 1) and the dashed line encircles the region of our data. The open triangles show reflected data points. The plot in the lower half was made with data of Ref. 1 alone, and the plot in the upper half with data from both experiments. The abscissa is the rapidity variable and ordinate is perpendicular momentum in units of $m_\pi c$. Contours are at intervals of 1 μb sr^1 MeV$^{-2.}$

about 0.6. Our π^- data are similarly flat over the acceptance region of our spectrometer.

The π^-/π^+ for Ar + Ca is 1.5 ±0.2 for data taken at the center of mass. Calculations by Cugnon and Koonin[9] predict the ratio R to be about 5.5 for Ar + Ca at this point. The structure predicted in their calculation is also inconsistent with our essentially flat spectrum. On the other hand, if they assume complete transparency, Libbrecht and Koonin[5] obtain a π^-/π^+ ratio at c.m. of $R \sim 1.7$, very close to our experimental results.

Calculations with Gyulassy and Kauffmann's[6] Eqs. (3.17), (3.20), (3.23), and (3.62) give $R \sim 1.6$ for the complete transparency case. Gyulassy furthermore ran his computer code for the Ar + Ca system, confirming the above transparency result and also giving a value of $R \sim 2.7$ for an impact-parameter-averaged fireball model. Radi *et al.*[10] have made trajectory calculations for the head-on complete transparency case, and they allow the pions to be emitted only at the last contact point of the nuclear spheres. For equal target and projectile charges Radi *et al.*[10] find for strictly symmetric collisions no Coulomb effect on the π^-/π^+ ratio ($R = 1$) for pions at rest in the center of mass, and they find $R \sim 1.045$ for the experimental charges of 18 and 20. In view of the differing results on Coulomb effects in the complete transparency case it appears that Coulomb effects can be very sensitive to details of the model at the time of pion creation, whether pions are allowed to propagate through nuclei without charge exchange, and so on.

In this connection we note that there is a neutron excess in ^{40}Ar, so simple counting of *nn* to *np* to *pp* collision ratios and decay modes of the Δ leads to $R \sim 1.15$. Stöcker points out[11] that thermodynamic considerations in hot nuclear matter that allow for condensation into clusters, such as α particles, lead to a primitive π^-/π^+ ratio (~ 1.35) for the ^{40}Ar plus ^{40}Ca system.

Since the data of Nagamiya *et al.*[12] are for Ar + KCl at $E/A = 800$ MeV, it is not possible to make a direct comparison. However, their relatively low π^-/π^+ ratios are quite consistent with our data. For example, their Fig. 30 shows the ratio nowhere exceeding 2, and their Table IV lists a total integrated cross section ratio of 1.4.

We have also taken data with carbon and uranium targets. The data on carbon are essentially flat, as are the data on uranium for π^+. The uranium π^- data have a slight falloff going forward from mid-rapidity. The invariant cross sections near nucleon-nucleon center-of-mass rapidity are as follows: For *C*, $\sigma_+ \sim 2.5$ μb sr^{-1} MeV^{-2}, $\sigma_- \approx 4.2$; for U, $\sigma_+ \approx 24$, $\sigma_- \approx 85$.

For the few data points at which our data directly overlap those of Wolf *et al.*[1] there is remarkable agreement. We disagree only on their lowest and third lowest energy data points at 30° (lab) reflected about the center of mass. Thus, our data do not corroborate their drop in invariant cross section with decreasing $p_\perp$ below $0.4 m_\pi c$.

The present data are very flat for both π^+ and π^- in the mid-rapidity region. The π^-/π^+ ratios and shapes are in disagreement with published theoretical predictions.

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*Present address: Physik-Institut der Universitat Zurich, Schonbergasse 9, 8001 Zurich, Switzerland.

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