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ARTICLES

Observation of Coulomb effects in production of $\pi^+\pi^-$, $p\pi^-$, and K^+K^- pairs in pp collisions at 27.5 GeV/c

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In a study of collisions of 27.5 GeV/c protons in liquid hydrogen we have observed enhanced production of oppositely charged hadron pairs when the relative velocity of the two hadrons in the pair rest frame approaches αc. The scale and velocity dependence of the enhancement agree well with the effect of the attractive Coulomb interaction as described by the Gamow factor.

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Although the electromagnetic interaction has long been predicted to modify observed phase-space densities for pairs of charged particles having a relative velocity in their rest frame of order αc [1–4], Coulomb effects between particles created in high-energy collisions, or in subsequent decays, continue to receive attention. For example, recent theoretical discussions include various predictions of their possible size and consequences in $\Upsilon_{4s}\rightarrow B\bar{B}$ decay [5,6] and in Bose-Einstein particle correlation studies [7,8], particularly in relativistic heavy-ion collisions [9,10], and treatment of $\pi^+\pi^-$ atomic bound states [11].

The velocity-dependent Coulomb modification of phase space is described by the Gamov factor $G(q)=2\pi\eta/(e^{2\pi\eta}-1)$, where $\eta=\alpha Z^+Z^-2\mu/q$, μ is the reduced mass ($1/\mu=1/m^+ + 1/m^-$), Z^+ and Z^- are the particle charges, and $\mathbf{q}$ is the three-momentum difference in the rest frame of the pair. When $q \ll \mu$, the corresponding velocity difference β^* is simply $\mathbf{q}/2\mu$. $G(q)$ has been used as a correction in the study of $K^\pm\rightarrow\pi^\pm\pi^+\pi^-$ decay [12] and same-sign pair correlations [13]. The first direct observation of the final-state Coulomb interaction in $\pi^+\pi^-$ pair production used 70-GeV/c protons on tantalum foil [14]. We report here the measurement of Coulomb effects in moderately high-multiplicity pp collisions for $\pi^+\pi^-$, $p\pi^-$, and K^+K^- pair production. The experimental signature is quite striking.

We analyzed 3×10^8 events containing on average 8 reconstructed charged particles that were produced in interactions of 27.5-GeV/c protons in liquid hydrogen at the BNL Alternating-Gradient Synchroton (AGS). Experiment 766 [15] used a large-aperture spectrometer (Fig. 1) to measure complex interactions at high rates. Six drift chambers of maximum drift distance 1–1.7 mm measured charged-particle trajectories in a nonuniform dipole magnetic field of central value 7.5 kG. Direct particle identification was provided by time-of-flight hodoscopes and by a 96-cell threshold Cherenkov counter ($\pi/K/p$ thresholds of 2.5/9.0/17.0 GeV/c). Track reconstruction was performed by a special purpose hardware processor [16].

We investigate the β^* dependence of $(+/-)$ pairs at small β^* using quantities that are independent of particle mass assignment. We directly measure $\mathbf{q}_\perp$, the relative momentum perpendicular to the pair momentum, and momentum asymmetry:

$$Y\equiv(|\mathbf{P}^+|-|\mathbf{P}^-|)/(|\mathbf{P}^+|+|\mathbf{P}^-|)\ ,$$

where $\mathbf{P}^+$ and $\mathbf{P}^-$ are the particles' laboratory momenta.

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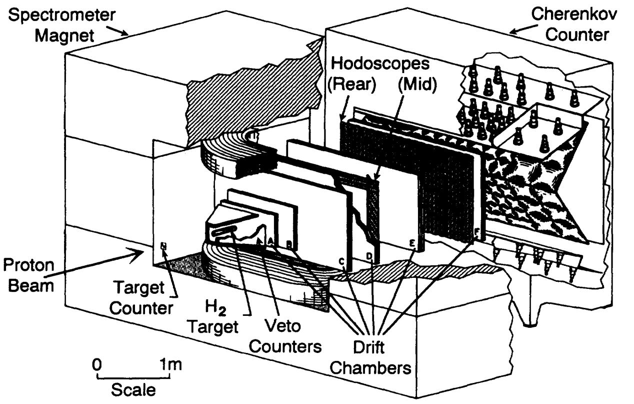

FIG. 1. Experiment 766 magnetic-field spectrometer.

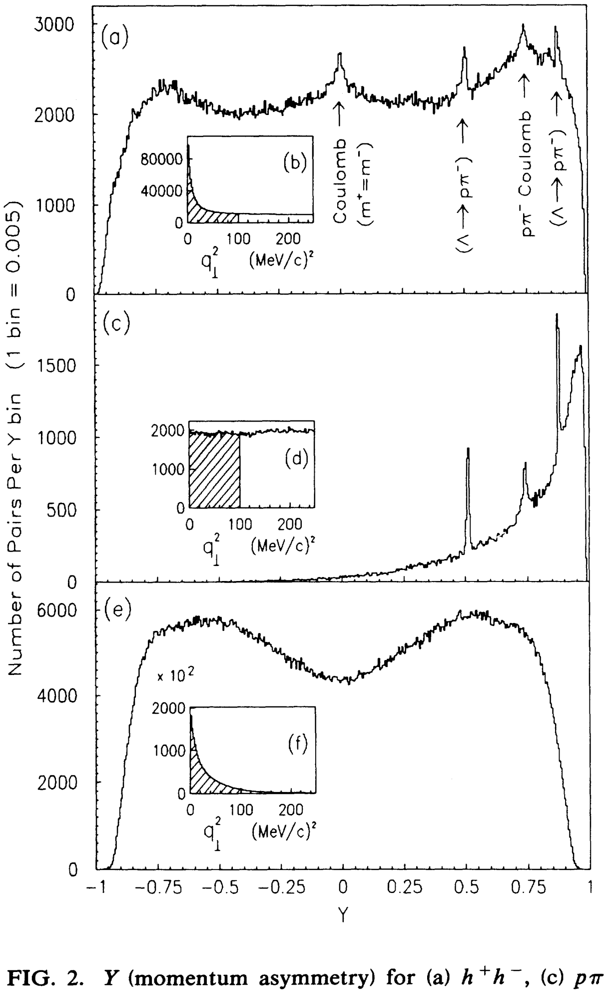

FIG. 2. Y (momentum asymmetry) for (a) h^+h^-, (c) $p\pi^-$, and (e) e^+e^- candidates with $q_\perp<10$ MeV/c. This $q_\perp$ region is shaded in the corresponding $q_\perp^2$ distributions [(b),(d),(f)]. The Y peaks at 0.0 in (a) and at 0.74 in (a) and (c) are evidence of enhanced production of the same mass (mostly $\pi^+\pi^-$) and $p\pi^-$ pairs with relative velocity in the pair rest frame approaching αc. Photon conversions to e^+e^- cause the forward peaks in $q_\perp^2$ [(b),(f)].

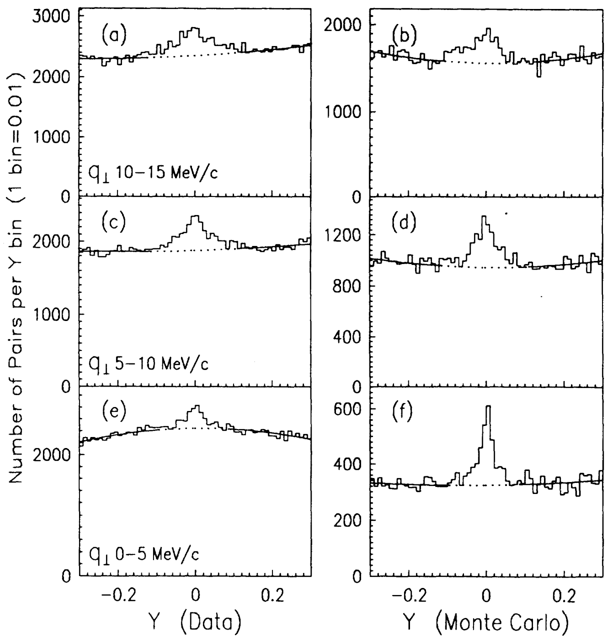

FIG. 3. Y (momentum asymmetry) for data h^+h^- candidates [(a),(c),(e)] and Monte Carlo $\pi^+\pi^-$ pairs [(b),(d),(f)] vs $q_\perp$.

For relativistic, small opening angle, small β^* pairs,

$$Y=\frac{m^+-m^-}{m^++m^-}+\left[\frac{\beta_\parallel^*}{2}\right]\left[\frac{2\mu}{m^+}\right]\left[\frac{2\mu}{m^-}\right]. \tag{1}$$

For small $q_\perp$, a narrow peak in Y centered at $(m^+-m^-)/(m^++m^-)$ provides a signature of enhanced production at small β^*.

We selected 8.4×10^6 $(+/-)$ pairs with $q_\perp^2<250$ (MeV/c)^2, neither particle assigned to more than one pair

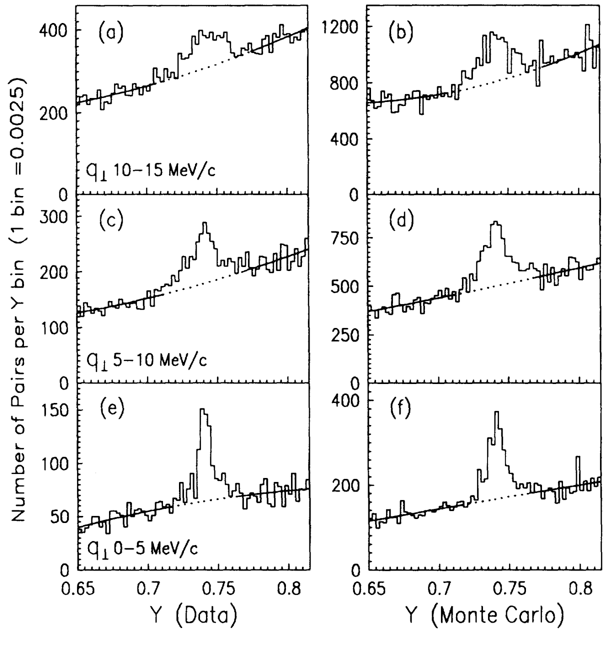

FIG. 4. Y (momentum asymmetry) for data $p\pi^-$ candidates [(a),(c),(e)] and Monte Carlo $p\pi^-$ pairs [(b),(d),(f)] vs $q_\perp$.

TABLE I. Y peaks at small β^* (see Figs. 3 and 4) for data (D) and Monte Carlo (MC) $\pi^+\pi^-$ and $p\pi^-$ pairs are compared as a function of $q_\perp$. Ex. Fr. denotes the fraction of total observed excess. Errors are statistical only.

	$q_\perp$ range		0–5 MeV/c	5–10 MeV/c	10–15 MeV/c
$\pi^+\pi^-$	Ex Fr	D	0.20±0.014	0.36±0.029	0.44±0.035
		MC	0.17±0.016	0.37±0.032	0.45±0.042
	rms	D	0.037	0.046	0.057
		MC	0.031	0.044	0.046
$p\pi^-$	Ex Fr	D	0.19±0.022	0.38±0.042	0.43±0.056
		MC	0.16±0.011	0.38±0.023	0.46±0.031
	rms	D	0.0085	0.012	0.014
		MC	0.0082	0.011	0.012

and both particles intersecting a vertex in the hydrogen formed by at least two additional tracks. These pairs are predominantly e^+e^- pairs from photons converting in material downstream of the primary vertex too close for the conversion to be resolved. These e^+e^- pairs have a softer momentum spectrum than hadron pairs and an apparent q_x (the horizontal component of q) shifted by twice the magnetic-field integral between the primary and actual conversion point. We used the Cherenkov counter to help select three samples: (1) h^+h^- candidates with $|\mathbf{P}^+ + \mathbf{P}^-| > 1$ GeV/c, $q_x < 0$, and neither particle identified as an $e^+(e^-)$; (2) $p\pi^-$ candidates, with the positive track identified as heavier than a pion; and (3) e^+e^- candidates with at least one particle identified as an $e^+(e^-)$.

Figure 2 shows the Y and $q_\perp^2$ distributions for the three samples. Four distinct Y peaks appear for the h^+h^- candidates [Fig. 2(a)]; the peak at 0.0 is the Coulomb effect for same mass pairs (predominantly $\pi^+\pi^-$) and the peak at $0.74 = (m_p - m_\pi)/(m_p + m_\pi)$ for $p\pi^-$ pairs. The other two peaks at 0.51 and 0.88 correspond to $p\pi^-$ pairs from unresolved axial Λ decays. The $p\pi^-$ peaks are more pronounced in the $p\pi^-$ sample [Fig. 2(c)]. No sharp structure is present for the e^+e^- sample [Fig. 2(e)]. (The shape is affected by the momentum dependence of electron identification.) The $q_\perp^2$ distributions [Figs. 2(b), 2(d), and 2(f)] indicate that e^+e^- pairs contaminate the h^+h^- sample at $q_\perp < 5$ MeV/c.

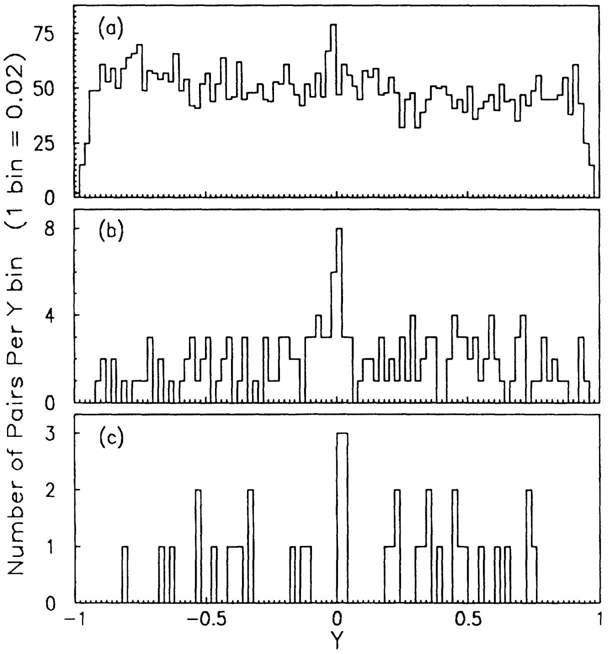

FIG. 5. Y (momentum asymmetry) for (a) $\pi^+\pi^-$, (b) K^+K^-, and (c) $p\bar{p}$ pairs with $q_\perp < 10$ MeV/c from fully reconstructed events.

To simulate the experimental effects of phase space modified by the Gamow factor, we generated pairs isotropically in $\mathbf{q}$ out to 100 MeV/c with the phase-space density modified by the Gamow factor: $dN/dq = q^2G(q)$. We then boosted the pairs into the laboratory frame using the momentum spectrum observed for the real data, added four tracks randomly selected from data to constrain the vertex position better, reconstructed the events including effects of material and digitization, and analyzed these simulated events in the same manner as the data. Our rms resolution for the $\pi^+\pi^-$ ($p\pi^-$) pairs in the h^+h^- ($p\pi^-$) sample is 3.5 (3.8) MeV/c in $q_\perp$ and 0.003 (0.002) in Y, considerably narrower than the dimensions of the enhancements. Note that the Y peaks from small β^* pairs are broader than those from unresolved Λ decays.

In Figs. 3 and 4, we compare the observed and simulated Y distributions for three regions of $q_\perp$: 0–5, 5–10, and 10–15 MeV/c. Except for h^+h^- candidates of $q_\perp < 5$ MeV/c, which include e^+e^- pairs smoothly varying in Y, the data and the simulated distributions are very similar. In Table I we describe the $q_\perp$ dependence by listing the rms width and fraction of the excess for each peak as determined by fitting the wings to a quadratic (solid line) and extending the fitted curve through the Y region containing the peak (dotted line). We find excellent agreement between the data and simulation for both the $\pi^+\pi^-$ and $p\pi^-$.

We also predict the absolute scale (No. of pairs) of the observed excess by normalizing the simulated excess [Monte Carlo (MC) peak] by the ratio of densities, (data pairs/V)/(MC pairs/V), over a much larger phase-space volume V outside the region contaminated by e^+e^- pairs or sharply modified by $G(q)$. V extends in $q_\perp^2$ between 187.5 and 250 (MeV/c)^2 and in Y from -0.3 to $+0.3$ for $\pi^+\pi^-$ pairs and from 0.65 to 0.815 for $p\pi^-$ pairs. If we assume that in V all h^+h^- candidates are $\pi^+\pi^-$ and all

TABLE II. Absolute scale in numbers of pairs of observed and predicted excess at small β^* for pairs with $q_\perp < 15$ MeV/c. MC peak, data/V, and MC/V are used in the normalization (see text).

	No. Observed	No. Predicted	MC peak	D/V	MC/V
$\pi^+\pi^-$	11 697±518	10 811±512	7574±359	70 460	49 365
$p\pi^-$	2574±161	2832±98	7675±265	10 669	28 912

$p\pi^-$ candidates are $p\pi^-$, we obtain the results listed in Table II. We note that the normalization technique is sensitive to uncertainties in hadron identification. For example, the discrepancy for the $p\pi^-$ can be explained if 8.9% of these candidates are $K^+\pi^-$ or pK^-: such pairs also satisfy the selection. For the h^+h^-, the pairs in the enhancement and in V are mostly $\pi^+\pi^-$. Any K^+K^- pairs would contribute a factor of 2.3 more enhancement than $\pi^+\pi^-$, and pairs of unequal mass, such as $p\pi^-$, contribute no enhancement at $Y=0$.

Finally, we present Y distributions for small opening angle $\pi^+\pi^-$, K^+K^-, and $p\bar{p}$ pairs (Fig. 5) from fully reconstructed events in which the pair and final-state topology were identified by application of conservation laws and direct particle identification. For the $\pi^+\pi^-$ pairs, we observe an enhancement of 53±20 pairs and predict 47. For the K^+K^- pairs, we observe an enhancement in the central two Y bins of 10.2±3.8 pairs and predict 5.2. Limited statistics preclude drawing a conclusion for the $p\bar{p}$ pairs. (The central two bins contain three pairs total, with a nearby average of 0.5 pairs/bin, compared with a prediction of 2.7 and 0.45 pairs/bin.)

In summary, in a sample of 3×10^8 reconstructed multiparticle events produced by collisions of 27.5-GeV/c protons in hydrogen, we have observed a sharp increase in the number of $\pi^+\pi^-$, $p\pi^-$, and K^+K^- pairs when the relative velocity of the two particles (in the pair rest frame) is of order αc. Our statistics and resolution for the $\pi^+\pi^-$ and $p\pi^-$ pairs are sufficient to show that this effect agrees in magnitude and dependence on the relative velocity with phase space modified by the Gamow factor as predicted for the attractive electromagnetic force. With limited statistics we observe the effect for K^+K^- pairs in fully reconstructed events.

Finally, we note that measurement of the final-state Coulomb interaction is relevant to the study of particles created near threshold. Also, modification of the Coulomb correction factor [the simplest form is $G(q)$] due to finite-size effects has been suggested as a possible probe of relativistic heavy-ion collisions [17].

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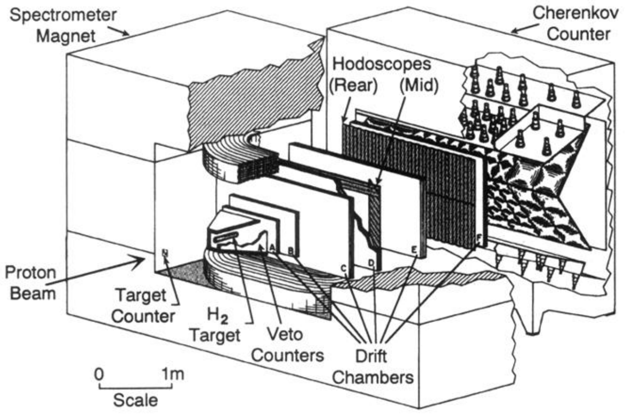

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