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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(Received 6 March 1992)

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 $ac$. The scale and velocity dependence of the enhancement agree well with the effect of the attractive Coulomb interaction as described by the Gamow factor.

PACS number(s): 13.85.Hd, 13.40.Ks

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 $ac$ \cite{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 \cite{5,6} and in Bose-Einstein particle correlation studies \cite{7,8}, particularly in relativistic heavy-ion collisions \cite{9,10}, and treatment of $\pi^+\pi^-$ atomic bound states \cite{11}.

The velocity-dependent Coulomb modification of phase space is described by the Gamov factor $G(q)$ \cite{2}.

$$G(q) = \frac{2\pi\eta}{e^{2\sigma\eta} - 1},$$

where $\eta = \alpha Z^+ Z^- 2\mu/q$, $\mu$ is the reduced mass $(1/\mu = 1/m^+ + 1/m^-)$, $Z^+$ and $Z^-$ are the particle charges, and $q$ is the three-momentum difference in the rest frame of the pair. When $q << \mu$, the corresponding velocity difference $\beta^*$ is simply $q/2\mu$. $G(q)$ has been used as a correction in the study of $K^+ \rightarrow \pi^+\pi^-\pi^-$ decay \cite{12} and same-sign pair correlations \cite{13}. The first direct observation of the final-state Coulomb interaction in $\pi^+\pi^-$ pair production used 70-GeV/c protons on tantalum foil \cite{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 $3 \times 10^8$ 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 Synchrotron (AGS). Experiment 766 \cite{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 \cite{16}.

We investigate the $\beta^*$ dependence of $(+/−)$ pairs at small $\beta^*$ using quantities that are independent of particle mass assignment. We directly measure $q_\perp$, the relative momentum perpendicular to the pair momentum, and momentum asymmetry:

$$Y = (|P^+| - |P^-|)/(|P^+| + |P^-|),$$

where $P^+$ and $P^-$ are the particles' laboratory momenta.
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 $q_1 < 10$ MeV/c. This $q_1$ region is shaded in the corresponding $q_1^2$ 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 $\alpha c$. Photon conversions to $e^+e^-$ cause the forward peaks in $q_1^2$ [(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 $q_1$.

FIG. 4. $Y$ (momentum asymmetry) for data $p\pi^-$ candidates [(a),(c),(e)] and Monte Carlo $p\pi^-$ pairs [(b),(d),(f)] vs $q_1$.

For relativistic, small opening angle, small $\beta^*$ pairs,

$$Y = \frac{m^+ - m^-}{m^+ + m^-} + \frac{\beta_s^2}{2} \begin{pmatrix} \frac{2\mu}{m^+} \\ \frac{2\mu}{m^-} \end{pmatrix}.$$  (1)

For small $q_1$, a narrow peak in $Y$ centered at $(m^+ - m^-)/(m^+ + m^-)$ provides a signature of enhanced production at small $\beta^*$.

We selected $8.4 \times 10^6$ $(+/-)$ pairs with $q_1^2 < 250$ (MeV/c)$^2$, neither particle assigned to more than one pair.
TABLE I. Y peaks at small β* (see Figs. 3 and 4) for data (D) and Monte Carlo (MC) π⁺π⁻ and ρπ⁻ pairs are compared as a function of q₁. Ex. Fr. denotes the fraction of total observed excess. Errors are statistical only.

<table>
<thead>
<tr>
<th>q₁ range</th>
<th>0–5 MeV/c</th>
<th>5–10 MeV/c</th>
<th>10–15 MeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>π⁺π⁻ Ex Fr</td>
<td>0.20±0.014</td>
<td>0.36±0.029</td>
<td>0.44±0.035</td>
</tr>
<tr>
<td>MC</td>
<td>0.17±0.016</td>
<td>0.37±0.032</td>
<td>0.45±0.042</td>
</tr>
<tr>
<td>rms</td>
<td>0.037</td>
<td>0.046</td>
<td>0.057</td>
</tr>
<tr>
<td>0.031</td>
<td>0.044</td>
<td>0.046</td>
<td></td>
</tr>
<tr>
<td>pπ⁻ Ex Fr</td>
<td>0.19±0.022</td>
<td>0.38±0.042</td>
<td>0.43±0.056</td>
</tr>
<tr>
<td>MC</td>
<td>0.16±0.011</td>
<td>0.38±0.023</td>
<td>0.46±0.031</td>
</tr>
<tr>
<td>rms</td>
<td>0.0085</td>
<td>0.012</td>
<td>0.014</td>
</tr>
<tr>
<td>0.0082</td>
<td>0.011</td>
<td>0.012</td>
<td></td>
</tr>
</tbody>
</table>

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 q₅ (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 |P⁺+P⁻| > 1 GeV/c, q₅ < 0, and neither particle identified as an e⁺(e⁻); (2) pπ⁻ 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 q₁ 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 π⁺π⁻) and the peak at 0.74=(m_p−m_π)/(m_p+m_π) for pπ⁻ pairs. The other two peaks at 0.51 and 0.88 correspond to pπ⁻ pairs from unresolved axial Λ decays. The pπ⁻ peaks are more pronounced in the pπ⁻ sample [Fig. 2(e)]. 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 q₁² distributions [Figs. 2(b), 2(d), and 2(f)] indicate that e⁺e⁻ pairs contaminate the h⁺h⁻ sample at q₁ < 5 MeV/c.

To simulate the experimental effects of phase space modified by the Gamow factor, we generated pairs isotropically in q out to 100 MeV/c with the phase-space density modified by the Gamow factor: dN/dq=q²G(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 π⁺π⁻ (pπ⁻) pairs in the h⁺h⁻ (pπ⁻) sample is 3.5 (3.8) MeV/c in q₁ 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 q₁: 0–5, 5–10, and 10–15 MeV/c. Except for h⁺h⁻ candidates of q₁ < 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 q₁ 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 π⁺π⁻ and pπ⁻.

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 q₁² between 187.5 and 250 (MeV/c)² and in Y from −0.3 to +0.3 for π⁺π⁻ pairs and from 0.65 to 0.815 for pπ⁻ pairs. If we assume that in V all h⁺h⁻ candidates are π⁺π⁻ and all

FIG. 5. Y (momentum asymmetry) for (a) π⁺π⁻, (b) K⁺K⁻, and (c) pp pairs with q₁ < 10 MeV/c from fully reconstructed events.
TABLE II. Absolute scale in numbers of pairs of observed and predicted excess at small $\beta^*$ for pairs with $q_i <$ 15 MeV/c. MC peak, data/$V$, and MC/$V$ are used in the normalization (see text).

<table>
<thead>
<tr>
<th></th>
<th>No. Observed</th>
<th>No. Predicted</th>
<th>MC peak</th>
<th>$D/V$</th>
<th>MC/$V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\pi^-$</td>
<td>11 697$\pm$518</td>
<td>10 811$\pm$512</td>
<td>7574$\pm$359</td>
<td>70 460</td>
<td>49 365</td>
</tr>
<tr>
<td>$p\pi^-$</td>
<td>2574$\pm$161</td>
<td>2832$\pm$98</td>
<td>7675$\pm$265</td>
<td>10 669</td>
<td>28 912</td>
</tr>
</tbody>
</table>

$p\pi^-$ 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 $53\pm20$ pairs and predict 47. For the $K^+K^-$ pairs, we observe an enhancement in the central two $Y$ bins of $10.2\pm3.8$ 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 $3\times10^5$ 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 $\alpha c$. 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].

We express our gratitude to A. Pendzick and his AGS crew for their support. We also thank W. A. Zajc for useful discussions. We wish to acknowledge the tireless dedication of Cicerio Avilez to establish an institute of experimental particle physics in Mexico. We regret his passing. This work was funded in part by the National Science Foundation under Grants Nos. PHY89-21320, PHY90-14879; the Department of Energy under Contracts Nos. DE-AC02-76CH03000, DE-AS05-87ER40356; and CONACyT de Mexico.

[17] W. A. Zajc (private communication).
FIG. 1. Experiment 766 magnetic-field spectrometer.