

Production of  $\rho^-$  in the Nuclear Coulomb Field\*

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The coherent process  $\pi^- + A \rightarrow A + \pi^- + \pi^0$  has been measured using nuclear targets. Sharp peaks are observed in the  $t'$  distributions. The  $\pi\pi$  mass spectrum is dominated by the  $\rho^-$  meson produced in the nuclear Coulomb field and by  $\omega^0$  exchange in the nuclear surface. The Coulombic process yields a measurement of the radiative width,  $\Gamma(\rho^- \rightarrow \pi^- + \gamma) = 35 \pm 10$  keV, which is in poor agreement with the simple unbroken-SU(3) prediction of 100 keV.

In an experiment performed at the Brookhaven National Laboratory using the spectrometer facility developed by the Lindenbaum-Ozaki group, we have measured the reaction<sup>1</sup>  $\pi^- + A \rightarrow A + \pi^- + \pi^0$  at a beam momentum of 22.7 GeV/c. The target nuclei C, Al, Cu, Ag, Pb, and U have been used.

Primakoff and Good and Walker<sup>2</sup> have pointed out that coherent Coulomb field reactions provide a measurement of the process  $x + \gamma \rightarrow x^*$ . In particular, the radiative widths of various hadronic resonances can be determined. Our primary motivation was the measurement of  $\Gamma(\rho^- \rightarrow \pi^- + \gamma)$ . Vector-meson radiative transitions are fundamental processes closely related to the magnetic properties of the quarks which are believed to underlie hadron structure.

Figure 1(a) shows in schematic form the detection geometry. Incident and final-state  $\pi^-$  were measured with counters and wire spark chambers.<sup>3</sup> Detection of the final  $\pi^-$  was restricted to the upper half-plane while the lower half-plane was reserved for  $\pi^0$  detection in an optical spark chamber. The target (0.1 to 0.25 radiation lengths in thickness) was surrounded by an almost  $4\pi$  system of veto counters constructed of interleaved sheets of scintillator and Pb. This arrangement suppressed triggers with superfluous hadron production or incoherent nuclear excitation.

Events are reconstructed *assuming* that the nuclear recoil energy was negligible as expected for coherent reactions. Consequently  $E_{\pi^0} = E_1$

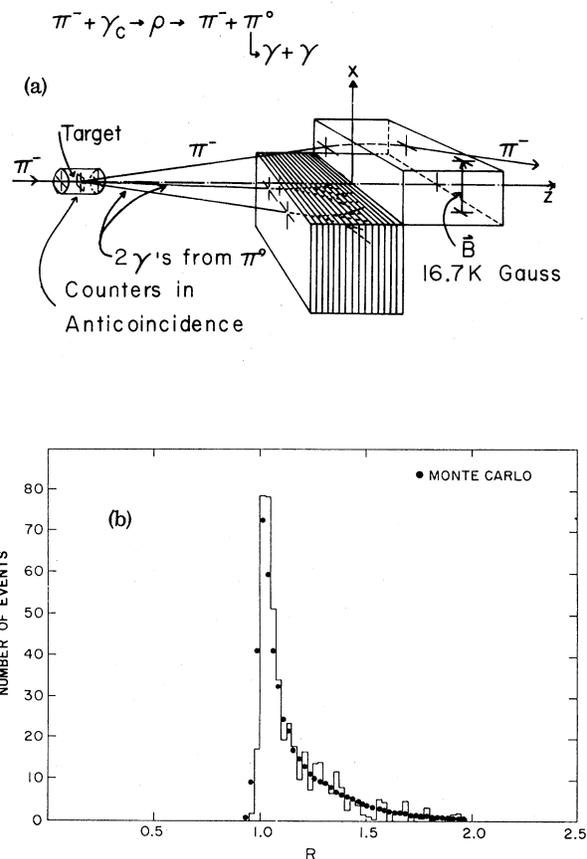


FIG. 1. (a) Schematic diagram illustrating the basic experimental geometry. (b)  $R$  distribution for  $\pi^-$  U data. The data have been subjected to the cuts  $E_\gamma > 1.0$  GeV and  $t' < 0.0116$  (GeV/c)<sup>2</sup>. Background has been subtracted and the Monte Carlo prediction is superimposed.

$-E_2$ , where  $E_1$  and  $E_2$  are the energies of the initial and final  $\pi^-$  each measured to an accuracy of  $\pm 0.25\%$ . The first signature of coherent reactions was the characteristic sharp Jacobian peak in the  $\pi^0$  opening-angle distribution. The sharp peak in effect confirms longitudinal momentum balance. The  $\gamma\gamma$  opening angle  $\theta$  was determined by the measured target vertex and the  $\gamma$ -ray shower vertices. A typical plot of the quantity  $R \equiv \sin(\theta/2)/\sin(\theta_m/2)$  is shown in Fig. 1(b). The minimum angle  $\theta_m$  is given by  $\sin(\theta_m/2) = m_{\pi^0}/E_{\pi^0}$ . The factor  $R$  determines the ratio of the  $\gamma$ -ray energies. An attempt to independently measure this ratio by estimating the relative strengths of the  $\gamma$ -ray showers proved to be quantitatively unreliable and was abandoned. Consequently a twofold ambiguity regarding the identity of the higher energy  $\gamma$  ray remained. We chose to use the solution producing the smaller value of  $t'$  (the square of the transverse momentum transfer). A slight artificial sharpening of the  $t'$  structure and a small smearing of the  $\pi^0\pi^-$  mass spectra and other experimental distributions resulted. The parametrized theoretical distributions were used as input to a Monte Carlo simulation of the experiment. The  $\gamma$ -ray energy mispairing effect was automatically corrected for by subjecting the Monte Carlo events to the same  $\gamma$  energy assignment criteria. Final data were subjected to the cuts  $E_\gamma > 1.0$  GeV and  $0.95 < R < 1.125$ .

The data of Fig. 1(b) have been corrected for a background of approximately 7% in the cut region. The largest subtraction was  $\approx 15\%$  for carbon data. The background was determined from the events in the regions  $R < 0.9$  and  $R > 2.0$  using a model based on the assumption that background originates from the reaction  $\pi^- + A \rightarrow A + \pi^- + \pi^0 + \pi^0$ . This reaction is closely related to the well-studied reaction  $\pi^- + A \rightarrow A + \pi^- + \pi^+ + \pi^-$ .<sup>4</sup> The  $2\pi^0$  reaction produces background when two of the four  $\gamma$  rays escape detection. The yield of events versus  $A$  with  $R < 0.9$  is in excellent agreement with the background model. Further confirmation of this model is afforded by the observation of events with three and four  $\gamma$  showers and the yield of large  $t'$  events. An empty-target subtraction ranging from  $< 2\%$  in C to 6.0% in U was also made.

Two measurements were performed with the apparatus which served as controls, checking efficiency, acceptance, and resolution. The first of these, the decay in flight of  $K^-(14 \text{ GeV}/c) \rightarrow \pi^- + \pi^0$ , is topologically similar to  $\rho^-$  decay and the decay rate is accurately known. The second con-

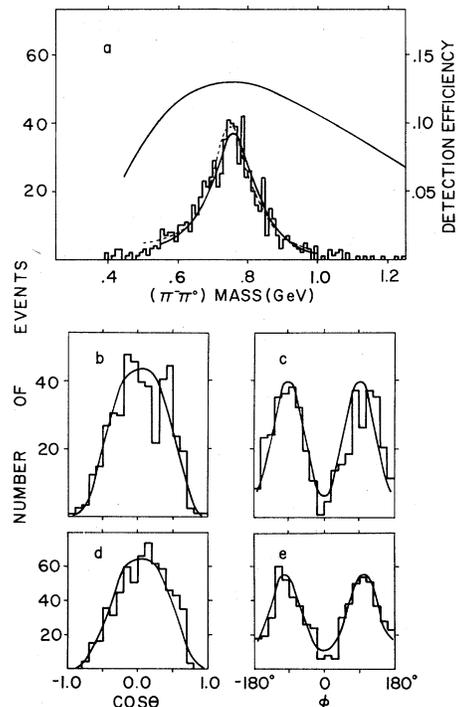


FIG. 2. (a) Mass acceptance of the apparatus and the  $\pi^-\pi^0$  mass distribution of the low  $t'$  events for Pb and U data combined. The best-fit values for the Coulomb model (solid curve) are  $m_0 = 768 \pm 3$  MeV,  $\Gamma_0 = 161 \pm 11$  MeV. The best-fit values for the hadronic model (dashed curve) are  $m_0 = 754 \pm 4$  MeV and  $\Gamma_0 = 130 \pm 9$  MeV. (b)–(e) The polar and azimuthal angle distributions in the Gottfried-Jackson frame with  $E_\gamma > 1.0$  GeV,  $0.95 \leq R \leq 1.125$ , and  $t' < t'_{\max} = 0.44A^{-2/3}$  (GeV/c)<sup>2</sup>. The solid lines are a Monte Carlo prediction based on a  $\sin^2\theta \times \sin^2\phi$  distribution; (b), (c) carbon data; (d), (e) Pb and U data.

trol was provided by the measurement of  $p(23 \text{ GeV}/c) + \gamma \rightarrow \Delta^+$ , using the same Coulomb field technique.<sup>5</sup> The cross section  $\sigma(\gamma + p \rightarrow \Delta^+)$ , or equivalently  $\Gamma(\Delta^+ \rightarrow p + \gamma)$ , is well known. The Coulomb production of  $\Delta^+$  was found to agree with photoproduction data to an accuracy of  $\pm 10\%$ .

Figure 2(a) shows the mass spectrum of the small- $t'$  data for U and Pb data combined. The yield is well fitted by a  $p$ -wave Breit-Wigner formula with parameters in agreement with compiled measurements.<sup>6</sup> The Coulomb and  $\omega^0$  exchange processes have slightly different mass dependences. Mass dependence enters through the square of the longitudinal momentum transfer,  $t_0 = (m^{*2} - m^2)^2/4p^2$ . The two superimposed curves in Fig. 2(a) correspond to the two exchange mechanisms. The true situation is a mixture of the two. The fit analysis indicates that the final state

is pure  $\rho^-$  with no more than 10% intensity of other coherently produced states. Note that Coulomb production of states with mass higher than the  $\rho^-$  is strongly suppressed by  $t_0$  dependence.

Figures 2(b)–2(e) show the measured distributions of decay angles in the center of mass of the  $\pi^- \pi^0$  system. The Gottfried-Jackson angles  $\theta$  and  $\varphi$  are displayed. The data are in good agreement with the  $\sin^2 \theta \sin^2 \varphi$  distribution expected for both Coulomb and  $\omega^0$  exchange. The  $\varphi$  distribution is determined by the recoil momentum of the nucleus ( $\vec{q}'$ ). This is typically  $\sim 50$  MeV/c for Pb and U. Thus the azimuth angle distribution is a convincing demonstration of the experimental  $\vec{q}'$  resolution ( $\approx 15$  MeV/c).

The background-subtracted  $d\sigma/dt'(A)$  distributions were fitted by a coherent superposition of Coulomb and nuclear amplitudes.<sup>7</sup> An optical model parametrization using a Woods-Saxon distribution for the nuclear density distribution  $\rho(\gamma)$  and including Coulomb phase shifts has been employed. We have used  $\sigma_{\rho N} = \sigma_{\pi N} = 26$  mb in the calculation of nuclear attenuation. The three fitting parameters are  $\Gamma(\rho^- \rightarrow \pi^- + \gamma)$ , the amplitude coefficient of the nuclear amplitude  $C_0$ , and the relative phase of the two amplitudes  $\varphi$ .

It was not possible to get a unique solution by fitting a single element. Sets of values for  $\Gamma$  and  $C_0$  are determined for each *ad hoc* choice of  $\varphi$ . Only the destructive-interference solution  $\varphi = 180^\circ \pm 45^\circ$  is clearly ruled out. On the basis of shape fits only, upper and lower limits for  $\Gamma$  of  $30 \pm 10$  and  $80 \pm 10$  keV can be inferred. Figure 3(a) illustrates for a particular set of parameters the  $t'$  dependence of the Coulomb and strong components. The former is more sharply peaked. The best-fit solid curve is the sum of the two dashed curves plus an interference term which is not shown. In the heavy elements it is clear that both components are present.

A unique solution is achieved if we require  $C_0$  to be independent of  $A$ . Figure 3(b) shows the solution obtained by fitting  $\sigma_T(A)$ . After weighing the uncertainties in normalization,  $t'$  resolution, optical model parameters, and statistical accuracy we conclude that  $\Gamma(\rho^- \rightarrow \pi^- + \gamma) = 35 \pm 10$  keV,  $C_0 = 4.0 \pm 1.0$  mb/(GeV/c)<sup>4</sup>,  $\varphi = 270^\circ \pm 45^\circ$ . The measured value for  $C_0$  is in agreement with a value of  $C_0 = 4.9 \pm 1.1$  mb/(GeV/c)<sup>4</sup> extrapolated from lower energy hydrogen data.<sup>8</sup>

There has been considerable theoretical speculation concerning vector-meson radiative decays.<sup>9</sup> The SU(3) symmetry scheme can be used to relate the various decays, while specific dynamical

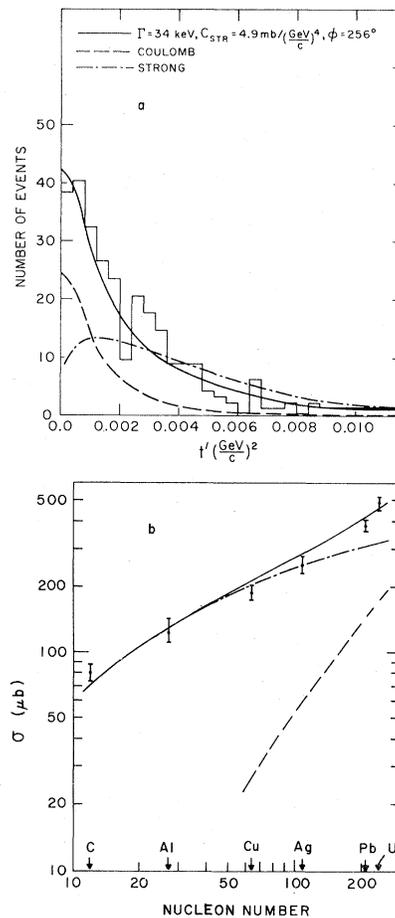


FIG. 3. (a) Background-subtracted angular distribution of the U data together with a particular acceptable fit. The Coulomb and strong production contributions are shown separately. (b) Integrated total cross sections [ $t' < t'_{\max} = 0.44A^{-2/3}$  (GeV/c)<sup>2</sup>] together with the result of the best fit obtained from the angular distributions.

schemes such as the pole model with vector dominance coupling constants or the quark model can be used to determine the absolute amplitudes. The only previously reported measurements,<sup>6</sup>  $\omega^0 \rightarrow \pi^0 + \gamma$  and  $\varphi^0 \rightarrow \eta^0 + \gamma$ , are in accord with the quark model although the predictions depend explicitly on vector and pseudoscalar meson mixing angles. Bemporad *et al.*<sup>7</sup> report an upper limit for  $\Gamma(K^{*+} \rightarrow K^+ + \gamma)$  of 80 keV (95% confidence level). Our measured value for  $\Gamma(\rho^- \rightarrow \pi^- + \gamma)$  is significantly smaller than various theoretical predictions which are typically 100 keV.<sup>9</sup>

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<sup>2</sup>The Coulomb field process was first discussed by H. Primakoff in connection with  $\gamma + \gamma \rightarrow \pi^0$  [Phys. Rev. **81**, 899 (1951)]. M. Good and M. Walker first discussed the general possibility of Coulomb field hadron dissociation [Phys. Rev. **120**, 1855 (1960)].

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<sup>6</sup>T. A. Lasinski *et al.*, Rev. Mod. Phys., Suppl. **45**, S1 (1973).

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<sup>8</sup> $C_0 = 13.7 \pm 2.2$  mb/(GeV/c)<sup>4</sup> at 5 GeV, D. J. Crennell *et al.*, Phys. Rev. Lett. **27**, 1674 (1971).  $C_0 = 6.9 \pm 1.5$  mb/(GeV/c)<sup>4</sup> at 16 GeV, J. Bartsch *et al.*, Nucl. Phys. **B46**, 46 (1972); an  $E^{-1}$  energy dependence has been assumed for extrapolation.

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## Discovery of a Second Narrow Resonance in $e^+e^-$ Annihilation\*†

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We have observed a second sharp peak in the cross section for  $e^+e^- \rightarrow$  hadrons at a center-of-mass energy of  $3.695 \pm 0.004$  GeV. The upper limit of the full width at half-maximum is 2.7 MeV.

The recent discovery of a very narrow resonant state coupled to leptons and hadrons<sup>1-3</sup> has raised the obvious question of the existence of other narrow resonances also coupled to leptons and hadrons. We therefore began a systematic search of the mass region accessible with the Stanford Linear Accelerator Center (SLAC)  $e^+e^-$  storage ring SPEAR and quickly found a second narrow resonance decaying to hadrons. The parameters of the new state [which we suggest calling  $\psi(3695)$ ] are

$$M = 3.695 \pm 0.004 \text{ GeV}, \quad \Gamma < 2.7 \text{ MeV}$$

[full width at half-maximum (FWHM)], where the mass uncertainty reflects the uncertainty in the absolute energy calibration of the storage ring.

The  $\psi(3695)$ , like the  $\psi(3105)$ , was found using the SLAC-Lawrence Berkeley Laboratory magnetic detector at SPEAR.<sup>4</sup> The luminosity monitoring, event acceptance criteria, and storage-ring energy determination have been described previously.<sup>1</sup>

The new feature of this run is the search procedure used to hunt for narrow  $e^+e^-$  resonances. In the search mode the storage-ring energy is increased in about 1-MeV steps ( $E_{c.m.} = 2 \times E_{beam}$ )