Measurement of the resonance parameters and radiative width of the ρ^+

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We present the results of new precision measurements of the radiative decay width, total width, and mass of the ρ^+ meson. These parameters are, respectively, 59.8±4.0 keV, 0.150±0.005 GeV, and 0.771±0.004 GeV, and were extracted from data obtained on the coherent production of ρ^+ in 200-GeV/c π^+ interactions with nuclear targets.

In this article we report our measurement of the radiative decay width of the ρ^+ meson: $\rho^+ \to \pi^+\gamma$. Decays of this kind have been used to test unitary-symmetry schemes and quark models of hadrons. The particularly simple radiative transition of relevance to our present discussion, namely, the decay of a vector meson (V) to a pseudoscalar meson (P) and a photon, proceeds through a magnetic dipole transition between two quark states; it is consequently sensitive to the symmetry properties of quark-antiquark systems. The phenomenology of such decays has been discussed extensively from the viewpoint of unitary symmetry,[1] quark models,[2] and vector-dominance approaches.[3] A recent summary of the experimental situation and of the phenomenology is available in Ref. 4.

Assuming the long-wavelength approximation, and complete overlap between initial- and final-state wave functions, the quark model yields the relation

$$\Gamma(V \to P\gamma) = \tfrac{4}{3} q^3 \mu^2 f(m_V, m_P) , \tag{1}$$

where q is the decay momentum in the rest frame of V, and μ is the matrix element of the magnetic moment operator between initial and final states. The form of the factor $f(m_V, m_P)$ is not fully known. Assuming that this factor has a weak mass dependence, its value can be set to unity[5] [$f(m_V,m_P) \sim f(m,m) = 1$]. A different choice is made in Ref. 4, namely, $f = E_P/m_V$ (E_P is the energy of the pseudoscalar in the vector-meson rest frame); this is justified through certain nonrelativistic approximations for the phase space. Clearly, this uncertainty in $f(m_V,m_P)$ affects the overall comparison between theory and experiment; it cancels out, however, in ratios of widths for radiative decays that have similar kinematics, e.g., $\Gamma(\rho \to \pi\gamma)/\Gamma(\omega \to \pi\gamma)$.

The radiative decay for the ρ^+ can be studied by measuring the inverse process of the coherent transition of a π^+ to a ρ^+ in the nuclear Coulomb field:[6]

$$\pi^+ + (A,Z) \to \rho^+ + (A,Z) , \tag{2}$$

where the final ρ^+ is observed in its $\pi^+\pi^0$ decay mode. The present data are from an experiment performed at Fermilab designed to study radiative decays of mesons. The procedures and conditions have been described elsewhere.[7] Briefly, the apparatus consisted of a high-resolution magnetic spectrometer and a fine-grained liquid-argon electromagnetic calorimeter. The experiment was performed at a π^+ beam momentum of 202.5 GeV/c, using carbon, copper, and lead targets of ~ 0.3 radiation lengths thickness.[8]

At high energy, the dominant contribution to reaction (2) is from single-photon exchange, although hadronic exchanges (e.g., ω^0 and A_2^0) are also possible. The presence of the photon propagator in the Coulombic part of the cross section leads to production at very small momentum transfers ($t \equiv |t| \approx 2t_{\min}$), and to a total yield that increases logarithmically with increasing energy. [Here, $t_{\min}$ is the minimum value of the square of the four-momentum transfer that is required to produce a $\pi^+\pi^0$ system of a given mass m. The approximate expression for $t_{\min}$ is $(m^2 - m_\pi^2)^2/4E_{\rm lab}^2$.] In contrast, the contribution from strong spin-flip exchange peaks at much larger t values ($t \approx 1/b$, where b is the slope of the nuclear form factor), and decreases with energy as $\sim 1/E_{\rm lab}$. At the energy of our measurement, the purely Coulombic contribution to reaction (2) comprises about 95% of the total ρ^+ production cross section for $t \le 0.002$ GeV^2. Because of differing dependences on t and target material, the contributions from strong and Coulomb production can be separated, and used to extract a very clean measurement of the ρ^+ radiative width, as well as other resonance characteristics (ρ^+ mass and total width).

The total coherent differential cross section for reaction (2) can be written as

$$\frac{d\sigma}{dt\,dm^2} = |\, T_C + e^{i\phi} T_S \,|^2 , \tag{3}$$

where T_C and T_S represent electromagnetic and strong amplitudes, and ϕ is the relative phase. Following Refs. 9 and 10, one obtains

$$|T_C|^2 = 24\pi\alpha Z^2 \frac{m^2}{(m^2-m_\pi^2)^3}\Gamma_\gamma \times \left[\frac{1}{\pi}\frac{m_\rho^2\Gamma_{\pi\pi}}{(m^2-m_\rho^2)^2+(m_\rho\Gamma_{\pi\pi})^2}\right] \times \frac{t-t_{\min}}{t^2}|F_{\mathrm{EM}}(t)|^2 \quad (4)$$

and

$$|T_S|^2 = A^2 C_S \left[\frac{1}{\pi}\frac{m_\rho^2\Gamma_{\pi\pi}}{(m^2-m_\rho^2)^2+(m_\rho\Gamma_{\pi\pi})^2}\right]|F_H(t)|^2 , \quad (5)$$

where m_ρ and $\Gamma_{\pi\pi}$ are the ρ^+ mass and width, respectively, and $F_{\mathrm{EM}}(t)$ and $F_H(t)$ stand for electromagnetic and hadronic coherent nuclear form factors (see Ref. 7 for details).

The extraction of the value of the ρ^+ radiative width proceeds through the fitting of Eqs. (3)–(5) to the momentum-transfer distributions given in Fig. 1. For this purpose, both theoretical and experimental distributions were integrated over the $\pi^+\pi^0$ mass range of 0.55–0.95 GeV, with the theoretical formulas smeared according to the experimental resolutions. Mass-dependent ρ^+ partial widths were assumed in the fits; the best parametrizations were $\Gamma_\gamma = \Gamma_{0\gamma}(q/q_0)^2(2q_0^2)/(q^2+q_0^2)$ and $\Gamma_{\pi\pi} = \Gamma_0(q/q_0)^3(2q_0^2)/(q^2+q_0^2)$, where q and q_0 are decay momenta for masses off and on resonance (q_0 being different for the $\pi\gamma$ and $\pi\pi$ channels); Γ_0 and $\Gamma_{0\gamma}$ are the values of the $\pi\pi$ and the $\pi\gamma$ widths of the ρ on resonance.

As seen in Fig. 1, the data exhibit sharp forward peaks that are characteristic of Primakoff production; the weaker dependence at larger t is due to strong coherent ρ^+ production. The two contributions were separated by treating $\Gamma_{0\gamma}$, C_S, and ϕ as free parameters. At this first stage, standard values[11] of $m_\rho = 770$ MeV and $\Gamma_0 = 150$ MeV were assumed in the fits. The results of fits to individual targets are displayed in Fig. 1, and the values obtained for the parameters are summarized in Table I, together with the result of a simultaneous global fit to the data on all three targets.

The globally fitted value for the ρ^+ radiative width ($\Gamma_{0\gamma}$) of 59.8±4.0 keV differs somewhat from a previous measurement by our group[7] of $\Gamma(\rho^-\to\pi^-\gamma) = 71\pm7$ keV. Although the present sample of ρ data is only about a factor of 2 larger than the first, the systematic errors on the present measurement are under far better control. The weighted average of our two measurements yields $\Gamma(\rho\to\pi\gamma) = 63\pm4$ keV, where statistical and systematic errors have been added in quadrature. This value is an agreement with a recent measurement of the radiative width of the ρ^- of 66.6±8.5 keV (Ref. 12). The fact that the extracted ρ^+ and ρ^- radiative widths are reasonably consistent with each other argues for dominance of the Primakoff mechanism and the lack of importance of strong and higher-order electromagnetic contributions (e.g., two-photon exchange) to the production process.

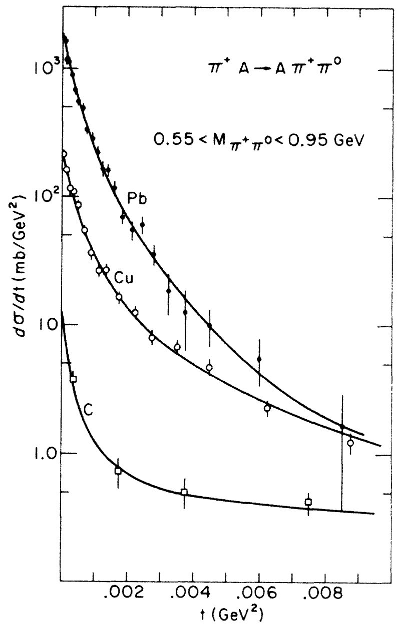

FIG. 1. Transverse-momentum distributions for data of reaction (2), and fits of Eq. (3) to the data.

In Table II we compare our result with theoretical expectations based on Eq. (1). The explicit form for the $\rho\to\pi\gamma$ transition is

$$\Gamma(\rho^+\to\pi^+\gamma) = \tfrac{4}{3}\alpha q_0^3(\tfrac{2}{3}\mu_u - \tfrac{1}{3}\mu_d)^2 f ,$$

where μ_u (μ_d) denotes the magnetic moment of the up (down) quark. We consider both unbroken SU(3) ($\mu_u=\mu_d=\mu_s$) and broken SU(3) (μ_u,μ_d,μ_s determined from p, n, and Λ magnetic moments). The results are presented for both choices of the factor f mentioned above, $f=1$ and $f=E_\pi/m_\rho$ (we refer the reader to the

TABLE I. Results of fits to t distributions. Errors in the table contain only statistical contributions.

Target	t range (GeV^2)	$\Gamma(\rho^+\to\pi^+\gamma)$ (keV)	C_s (mb/GeV^2)	ϕ (degrees)	χ^2/DF
C	<0.04	47.3±7.0	0.54±0.07	0±93	0.7/4
Cu	<0.01	59.5±1.9	0.24±0.08	15±40	14.2/13
Pb	<0.01	59.3±1.6	1.43±0.55	87±11	13.5/20
Global	<0.01	59.8±1.2	0.34±0.13	41±24	35.9/40

TABLE II. Comparison of data with predictions from SU(3). Errors in the table contain systematic as well as statistical uncertainty. Results are in keV.

	Experiment	Unbroken SU(3)	Broken SU(3)
$\Gamma_\gamma(\rho)$, $f=1$	63 ± 4	123	110
$\Gamma_\gamma(\rho)$, $f=E_\pi/m_\rho$	63 ± 4	64	57
$\Gamma_\gamma(\omega)/\Gamma_\gamma(\rho)$	12.5 ± 1.7	9.6	10.9

original papers[4,5] for discussion of the physical motivations). Finally, we also give the values of the ratio of radiative widths of the ρ^+ and ω^0; as mentioned previously, due to similar decay kinematics and identical quark content of the ρ and ω, the f factors cancel almost completely in this ratio. In Table II we used the value $\Gamma(\omega^0\rightarrow\pi\gamma)=789\pm92$ keV of Ref. 13. As can be seen from Table II, the radiative width of the ρ is more consistent with theory when the phenomenological factor f is set to E_π/m_ρ. However, the value of Γ_γ, and the ratio of $\Gamma_\gamma(\omega)/\Gamma_\gamma(\rho)$, do not distinguish between the predictions of broken or unbroken SU(3). We wish to point out, however, that a recent measurement[14] of the radiative width of the $K^*(890)^0$, in comparison with our previous measurement[15] of the radiative width of the $K^*(890)^+$, appears to be in better agreement with predictions of broken symmetry.

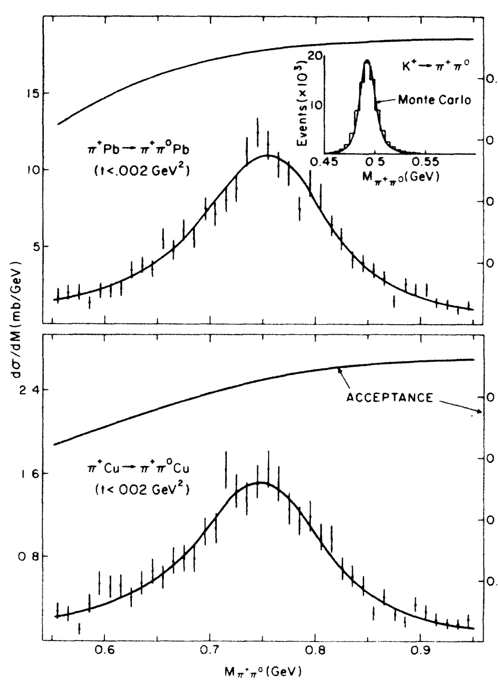

FIG. 2. Mass distributions for $\pi^+\pi^0$ coherent production on Cu and Pb, and fits used for establishing the ρ^+ mass and full width. The inset displays the mass distribution observed for tagged $K^+\rightarrow\pi^+\pi^0$ decays in the beam, and, for comparison, a Monte Carlo simulation of the expected distribution.

TABLE III. Mass and width of the ρ^+. Errors in table contain only statistical contributions.

	m_ρ (GeV)	$\Gamma(\rho^+\rightarrow\pi^+\pi^0)$ (GeV)
Cu	0.768 ± 0.003	0.152 ± 0.008
Pb	0.773 ± 0.002	0.149 ± 0.006
Average	0.771 ± 0.002	0.150 ± 0.005

We now present our results for the ρ^+ mass and its $\pi^+\pi^0$ decay width. Having shown that the t distributions are well described by our theoretical expressions, we introduced our extracted values of $\Gamma_{0\gamma}$, C_S, and ϕ into Eq. (3), and allowed m_ρ and Γ_0 to vary. In these fits we used only the high-statistics data samples obtained with Cu and Pb targets, and restricted the data to $t<0.002$ GeV^2, so as to enhance the Coulomb component. The results of these fits are shown in Fig. 2, and the final values of the fitted parameters are given in Table III. We note that the expected resonance-shape distortion, due to mass-dependent factors (other than just the Breit-Wigner term) in the Primakoff-production formula [Eq. (4)], is clearly seen in the data. Combining the results for the two targets (weighted average), we obtain $m_\rho=0.771\pm0.004$ GeV and $\Gamma(\rho^+\rightarrow\pi^+\pi^0)=0.150\pm0.005$ GeV, where the errors reflect statistical and systematic uncertainties added in quadrature. These parameters, extracted from data in a clean and unique regime of production, agree with the corresponding world-average values of Ref. 11.

We have varied the t ranges used in the fits, and have investigated the sensitivity of the extracted parameters to uncertainties in the resolution, as well as to the forms used for the mass-dependent widths. Changing the t ranges provides typical changes in Γ_γ of $\pm2\%$; uncertainty in the resolution (primarily in t) contributes to an uncertainty in Γ_γ of $\sim1\%$; shifting the mass and width of the ρ^+ by one standard deviation from their fitted values, provides uncertainties of $\sim1-1.5\%$ in Γ_γ. For reasonable fit-χ^2 values, different functional forms for $\Gamma_{\pi\pi}$ or Γ_γ do not directly affect the radiative width, but change m_ρ and $\Gamma(\rho^+\rightarrow\pi^+\pi^0)$ by about 8 and 2 MeV, respectively. As a check on systematics, we show in Fig. 2 our data for $K^+\rightarrow\pi^+\pi^0$ decays (taken simultaneously with the ρ^+ events, and used for normalizing the ρ^+ yield), and a Monte Carlo simulation of these in-flight decays; good agreement is observed, which demonstrates that the $\pi^+\pi^0$ mass scale, the resolution, and the efficiency corrections in our experiment are reliable.[8] [We should also point out that the uncertainty on the absolute normalization of the Primakoff method has been checked using our data on pion Compton scattering in the Coulomb field ($\pi^+ + A\rightarrow\pi^+\gamma + A$), and found to be good to at least 8% accuracy.[16]]

We conclude on the basis of our precision measurements of coherent ρ production on nuclear targets that the best value of the radiative width of the charged ρ meson is 63 ± 4 keV, its resonance mass is 0.771 ± 0.004 GeV, and its total width is 0.150 ± 0.005 GeV.

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