Phys. Rev. D 9, 3357 (1974); L. Dolan and R. Jackiw, Phys. Rev. D 9, 2904 (1974); C. Bernard, Phys. Rev. D 9, 3312 (1974); D. A. Kirzhnitz and A. D. Linde, Ann. Phys. (N.Y.) 101, 195 (1976). For a review, see A. D. Linde, Rep. Prog. Phys. 42, 389 (1979).

[13]It is a standard problem that spontaneous symmetry breaking yields an enormous cosmological constant [M. Veltman, unpublished; J. Dreitlein, Phys. Rev. Lett. 33, 1243 (1974)]. However, this effect is negligible compared to the energy density of order NT^4 when N is large (see S. Bludman and M. Ruderman, Phys. Rev. Lett. 38, 255 (1977).

[14]Weinberg, Ref. 12; R. N. Mohapatra and G. Senjanović, Phys. Rev. Lett. 42, 1651 (1979).

[15]Indeed, real systems with this behavior actually exist. An example often quoted is that of Rochelle salt. F. Jonq and G. Shirane, *Ferroelectric Crystals* (Pergamon, Oxford, 1962), p. 280.

[16]The scalar curvature couples to both φ^2 and η^2. However, at high temperatures the behavior of G is dominated by φ^2 and η^2 is going to zero.

[17]In particular, I did not include a vacuum energy of the order $-(\lambda_3+\lambda_1)^2\lambda_1^{-1}T^4$ which is negligible provided that N is large. Similarly, the curvature correction ($k\neq\pm1$, footnote 4) is negligible.

[18]Barrow, Ref. 2, and references therein; S. Bludman, private communication.

[19]M. Yoshimura, Phys. Rev. Lett. 41, 381 (1978), and to be published; S. Dimopoulos and L. Susskind, Phys. Rev.D 18, 4500 (1978); D. Toussaint, S. Treiman, F. Wilczek, and A. Zee, Phys. Rev. D 19, 1036 (1979); S. Weinberg, Phys. Rev. Lett. 42, 850 (1979); J. Ellis, M. K. Gaillard, and D. Nanopoulos, Phys. Lett. 80B, 360 (1978); A. Y. Ignatiev, N. Y. Krosnikov, V. A. Kuzmin, and A. N. Tavkhelidze, Phys. Lett. 76B, 436 (1978); S. Barr, G. Segrè, and A. Weldon, University of Pennsylvania Report No. UPR-0127T, 1979 (to be published); D. Nanopoulos and S. Weinberg, to be published; A. Yildiz and P. Cox, to be published.

[20]This point has also been made by S. Turner, Nature 281, 549 (1979).

[21]S. Coleman and E. Weinberg, Phys. Rev. D 7, 1888 (1973).

[22]M. Marciano, Phys. Rev. D 20, 274 (1979); T. Goldman and G. Ross, to be published.

[23]S. Weinberg, Phys. Lett. 82B, 387 (1979); K. T. Mahanthappa, M. A. Sher, and D. G. Unger, Phys. Lett. 84B, 113 (1979), and references therein.

Radiative Width of the ρ^- Meson

D. Berg, C. Chandlee, S. Cihangir, T. Ferbel, T. Jensen, F. Lobkowicz, C. A. Nelson,[(a)] T. Ohshima, P. Slattery, and P. Thompson
University of Rochester, Rochester, New York 14627

and

J. Biel, T. Droege, A. Jonckheere, and P. F. Koehler
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

S. Heppelmann, T. Joyce, Y. Makdisi,[(b)] M. Marshak, E. Peterson, K. Ruddick, and T. Walsh
University of Minnesota, Minneapolis, Minnesota 55455
(Received 31 October 1979)

The excitation of high-energy pions in the nuclear Coulomb field has been investigated. The data, analyzed assuming the presence of both electromagnetic and strong contributions to coherent production of $\pi^-\pi^0$ systems, yield a decay width for $\rho^-\to\pi^-\gamma$ of 67 ± 7 keV.

A long-standing difficulty in our understanding of radiative transitions between vector-meson and pseudoscalar-meson states has been the small value of $\Gamma_\gamma=35\pm10$ keV measured for the decay width of $\rho^-\to\pi^-\gamma$.[1] Although several attempts have been made to reconcile the expected theoretical prediction[2] of ~90 keV with the results of this measurement, these have been far from satisfying.[3] In order to substantiate the results of the previous experiment, we undertook to repeat the measurement, but at a higher energy, where background from nonelectromagnetic processes is less significant.

We have determined Γ_γ using the inverse process $\pi^-\gamma\to\rho^-$, where the Coulomb field of a heavy nucleus (of charge Z) is employed as a source of photons. The specific reaction we studied was

$$\pi^- + Z \to \pi^- + \pi^0 + Z. \qquad (1)$$

The experimental setup, shown in Fig. 1(a),

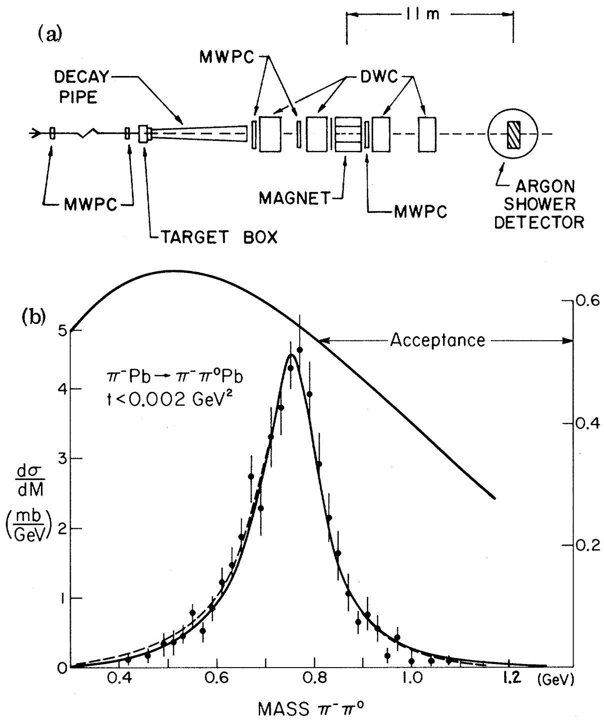

FIG. 1. (a) Schematic diagram of the experimental setup. (b) Mass distribution for Reaction (1) at 156 GeV/c. The two smooth curves correspond to fits with use of different parametrizations for the p-wave mass dependence. These fits differ appreciably only far from the resonance mass. The acceptance is calculated assuming $\sin^2\theta$ decay for the ρ^-. The data have been corrected for acceptance and target-empty rates.

was a spectrometer comprised of elements that could detect both charged particles and photons. The incident beam was defined by two sets of multiwire proportional counters (MWPC's) and several scintillation counters; three Cherenkov counters (not shown) were utilized to tag incident pions, kaons, and protons. Two arrays of drift chambers, located upstream and downstream of an analyzing magnet, were used to measure momenta and directions of forward-going charged hadrons. A 6-m-long vacuum pipe downstream of the target enabled us to normalize our data to K^- decays in flight. A liquid-argon electromagnetic shower detector was used to measure positions and energies of photons. With use of the electron component of the beam at 50 GeV, the energy resolution of the photon detector was determined to be $\pm[(15\ \text{GeV}^{1/2})/\sqrt{E}]\%$ (the spatial resolution was $\pm 900\ \mu$m). The spatial resolution of the drift chambers was found to be $\pm 220\ \mu$m. The overall resolution in transverse momentum for the $(\pi^-\pi^0)$ system varied between 12 and 21 MeV/c (standard deviations), depending on target and incident momentum.

Veto counters positioned around the target and the decay vacuum pipe and at the aperture of the magnet were used to reduce background from multiparticle interactions. Triggers resulting from interactions in material downstream of the target or from small-angle elastic scatters were suppressed by a vetoing matrix between beam-defining MWPC's and the MWPC located at the end of the decay pipe. The liquid-argon calorimeter was also included in the trigger; in particular, we required the presence of at least 10 GeV of neutral energy in the front 13 radiation lengths of the detector.

Data were obtained using copper and lead targets at 260 GeV/c, and carbon, aluminum, copper, and lead targets at 156 GeV/c. Different thicknesses of lead and copper targets were used to assess possible systematic effects. About 50 000 $K^- \to \pi^-\pi^0$ decays in flight, taken simultaneously with the ρ^- data, were used to check the normalization and resolution and the acceptance of the spectrometer. The characteristics of these K^- decays were examined in detail and found to be in excellent agreement with those expected. Because the topologies for $\rho^- \to \pi^-\pi^0$ and for $K^- \to \pi^-\pi^0$ decays are quite similar, we have normalized all our yields to the observed K^- decays. This has the virtue of eliminating reliance on calculations of absolute efficiencies. The acceptance is a function of the $\pi^-\pi^0$ mass as well as of the decay characteristics of the di-pion. Because corrections depend on the nature of the assumed angular decay distribution, we examined the polar decay angles of ρ^- events at small t and found the expected $\sin^2\theta$ form for a p-wave $\pi\pi$ final state.[4] The corresponding distribution for K^- decays is consistent with isotropy.[5]

Figure 1(b) displays the $\pi^-\pi^0$ masses for Reaction (1) at 156 GeV/c, utilizing a lead target. The data are for $t < 0.002$ GeV^2, where electromagnetic production dominates the reaction. A clear ρ^- signal is apparent.

Figure 2 displays t distributions for $\pi^-\pi^0$ masses between 0.55 and 0.95 GeV, for several nuclear targets, at an incident momentum of 156 GeV/c. The sharp maxima near $t=0$ are characteristic of electromagnetic production, and the slower falloffs at larger t are characteristic of coherent nuclear processes. The acceptance of the apparatus is essentially independent of t

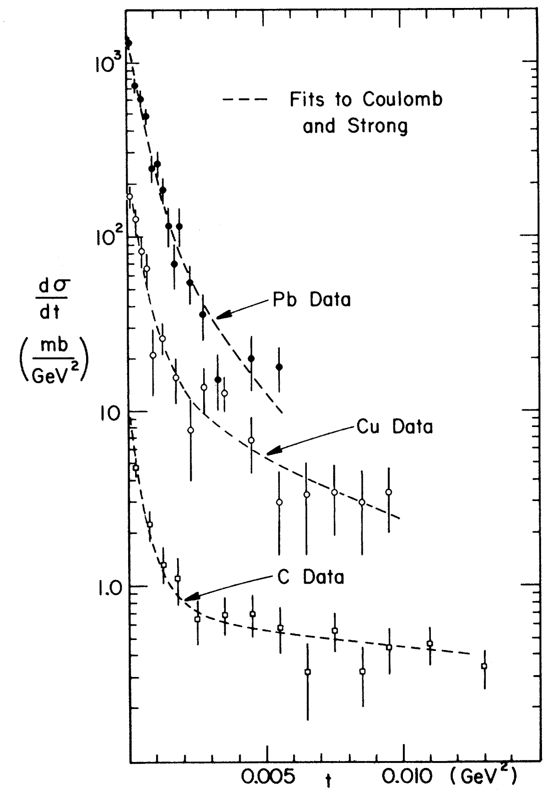

FIG. 2. Typical fits to t distributions at 156 GeV/c. The data have been corrected for acceptance and for target-empty rates.

for the interval shown.

We have analyzed Reaction (1) assuming contributions from both electromagnetic (Primakoff process) and hadronic (ω^0 exchange) amplitudes. Schematically, one can write

$$d\sigma/dt = |F_C + e^{i\varphi}F_S|^2 + D\exp(-E|t|), \qquad (2)$$

where F_C and F_S represent, respectively, the amplitudes for Coulomb and strong ρ^- production, φ is the relative phase between these amplitudes, and the remaining term is included to accommodate any other sources of ρ^- production (E is a parameter, not the energy). We assumed that $|F_S|^2$ was proportional to an adjustable coefficient C_S; since the basic formalism we employed has been presented elsewhere, we do not provide any further details here.[6]

From a fit of the mass spectrum [Fig. 1(b)] to the Primakoff formula using a p-wave line shape, we obtained 776 ± 4 MeV and 149 ± 8 MeV for the ρ^- mass and width, respectively. These values are in good agreement with those presented in the Particle Data Tables.[7] The data, integrated over the ρ^- mass, were fitted as a function of t by Eq. (2) with corrections made for experimental resolution. Typical fits are shown in Fig. 2.

Table I summarizes the results. The parameters are insensitive to the presence of the background term in Eq. (2). (D and E are not tabulated becuase the background term is $\lesssim 1\%$ at small t.) In the global fits (for $t < 0.01$ GeV^2), we ignore background and assume that C_S and φ are independent of target material.[8] All fits yield acceptable χ^2 values. For completeness, we tabulate the integrated values of $|F_S|^2$, $|F_C|^2$, and the interference term, for $t < 0.005$ GeV^2. The uncertainties quoted in the table are statistical only.

The largest systematic error in fits to lead data stems from uncertainty in the experimental resolution; we estimate that this contributes a ± 8% error to Γ_γ. The other target materials are subject to further uncertainty due to ambiguities in parametrization of F_S; this is particularly true for targets of small Z. The overall uncertainty, even for carbon, however, we believe to be less than ± 20%.

TABLE I. Results of parametrization of data (all quoted errors are statistical).

P_{inc}	Target	t range (GeV^2)	Γ_γ (keV)	C_S (mb/GeV^4)	φ	$\int_0^{0.005}|F_C|^2dt$ (μb)	$\int_0^{0.005}|F_S|^2dt$ (μb)	$2\mathrm{Re}\int_0^{0.005}F_C^*F_Se^{i\varphi}dt$ (μb)
156 GeV/c	Carbon	< 0.08	55.6 ± 5.9	0.58 ± 0.06	−5 ± 54	5.9 ± 0.6	0.6 ± 0.1	1.8 ± 0.2
	Aluminum	< 0.06	68.3 ± 7.3	0.55 ± 0.16	−7 ± 132	33 ± 4	2.0 ± 0.6	7.7 ± 2.5
	Copper	< 0.04	61.1 ± 5.0	0.62 ± 0.15	37 ± 30	137 ± 11	7.4 ± 1.8	19.8 ± 8.2
	Lead	< 0.04	70.8 ± 3.6	0.32 ± 0.25	65 ± 24	1082 ± 55	12.0 ± 9.4	11.3 ± 11.0
	Global fit	< 0.01	63.4 ± 2.9	0.53 ± 0.07	14 ± 35			
260 GeV/c	Copper	< 0.06	65.8 ± 8.4	0.07 ± 0.23	183 ± 137	175 ± 22	0.9 ± 2.9	−9.5 ± 15.7
	Lead	< 0.04	71.6 ± 3.9	1.06 ± 0.37	61 ± 21	1349 ± 74	33.7 ± 11.8	29.7 ± 20.5
	Global fit	< 0.01	72.4 ± 3.4	0.72 ± 0.25	74 ± 18			

In conclusion, our overall best estimate for the ρ^- radiative width is 67 ± 7 keV, where the uncertainty reflects both experimental errors and theoretical ambiguities in the formalism.[9] This result is substantially higher than that reported in Ref. 1. There is less than a 1% likelihood that both experiments are correct within their quoted errors. The present experiment is an improvement over the earlier effort in several important respects: (1) At out energies the ratio of Coulomb-to-hadron exchange is greatly enhanced relative to its value at 23 GeV/c. This enabled us to obtain stable and consistent fits for our individual target elements and at our two incident energies. In contrast, the previous authors were only able to extract a unique partial width after carrying out a global fit to all their elements assuming a constant value of C_S. Without this assumption, only an upper limit of 80 ± 10 keV was reported, a value which is in complete agreement with our result. It is interesting to note that a variation of C_S with A has some theoretical basis, particularly at lower beam energies.[8] (2) We *continuously* normalized our data using a large sample of K^- decays, and consequently our analysis is insensitive to a host of otherwise troublesome experimental difficulties. In contrast, the previous investigators used a small sample of K^- decays taken at 14 GeV/c for this purpose, and consequently had to employ a larger and intrinsically less reliable extrapolation. (3) Our apparatus was technically superior, especially in our ability to measure neutrals. In particular, we measured both the energies and positions of all photons striking our liquid-argon detector. In contrast, the earlier experimenters employed an optical spark chamber to detect showers and were therefore only able to determine photon positions. As a consequence, they were unable to use overall energy balance to reject multi-π^0 events (e.g., from A_1^- production), a capability which we found valuable. Moreover, because of the lack of γ-energy information, a two-fold ambiguity was introduced into their π^0 reconstruction, which had to be resolved in favor of the lower-t solution. Unfortunately, this produces a distortion of the resultant t distribution, which is the primary input into the ultimate fitting program. While these difficulties were recognized and intelligently addressed in the previous experiment, they unquestionably complicated the overall analysis. If for the above reasons our measurement of Γ_γ is preferred over the previous value, it is interesting to note that it is thereby possible to obtain a far more self-consistent overall fit to vector meson radiative widths.[10]

We thank Dr. T. Toohig, Dr. A. Brenner, Dr. A. Greene, Dr. J. Peoples, Dr. A. Wehman, and Dr. T. Yamanouchi of Fermilab for their support of our experiment. This research was supported by the U. S. Department of Energy, the National Science Foundation, and funds from the Universities of Minnesota and Rochester.

---

[a]Presently at Fermi National Accelerator Laboratory, Batavia, Ill. 60510.

[b]Presently at Brookhaven National Laboratory, Upton, N. Y. 11973.

[1]B. Gobbi *et al.*, Phys. Rev. Lett. 33, 1450 (1975), and 37, 1439 (1976).

[2]Assuming unbroken SU(3) symmetry and ideal singlet-octet mixing, the radiative transition of the ω^0 and ρ^- can be related to yield $\Gamma(\rho^- \to \pi^-\gamma)/\Gamma(\omega^0 \to \pi^0\gamma) \approx \frac{1}{9}$. See, for example, C. Becchi and G. Morpurgo, Phys. Rev. 140B, 687 (1965).

[3]See, for example, B. J. Edwards and A. N. Kamal, Phys. Rev. D 15, 2019 (1977); A. N. Kamal, Phys. Rev. D 18, 3512 (1978); A. Bohm and R. B. Teese, Phys. Rev. D 18, 330 (1978); M. Bando *et al.*, Prog. Theor. Phys. 59, 903 (1978).

[4]The expected azimuthal dependence is $\sin^2\varphi$. At these energies resolution dominates the φ distribution at small t. However, carbon data, at larger t values, do exhibit this predicted shape.

[5]See T. Jensen *et al.*, in Proceedings of the Ninth International Meeting of Leptons and Photons—1979, edited by H. Abarbanel and T. Kirk (to be published). We also obtained consistent results using K_{e3} decays. In addition, we checked our normalization by measuring the yield of Coulomb-produced $\Delta^+(1232)$ in the p-Pb channel. In this case, the radiative width of the $\Delta^+(1232) \to p\gamma$ is known to high precision. [See R. L. Walker, Phys. Rev. 182, 1729 (1969) and P. Feller *et al.*, Nucl. Phys. B104, 219 (1976).] Our $\Delta^+(1232)$ yield is consistent to better than $\pm 5\%$ with expectations from the Primakoff formula.

[6]See C. Bemporad *et al.*, Nucl. Phys. B51, 1 (1973); G. Fäldt, Nucl. Phys. B43, 591 (1972). The parametrization used in this paper is essentially that of Fäldt. Our definition of C_s agrees with that used for C_0 in Ref. 1; physically, $C_s^{1/2}$ measures the strength of ω exchange for a single nucleon target.

[7]C. Bricman *et al.*, Phys. Lett. 75B, 1 (1979).

[8]A. N. Kamal and G. L. Kane, Phys. Rev. Lett. 43,

[9]We might point out that using δ-function approximation for the ρ^-, rather than a resonant form, reduces Γ_γ by ~11% (for a ρ^- mass of 776 MeV). Also, a change of ± 10 MeV in the mass changes Γ_γ by about $\pm 5\%$.

[10]See T. Ohshima, University of Rochester Report No. UR-733, 1980 (unpublished); also B. J. Edwards and A. N. Kamal, Stanford Linear Accelerator Center Report No. SLAC-PUB-2303, 1979 (unpublished).