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DETERMINATION OF STRONG-INTERACTION NUCLEAR RADII*

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We present results on the determination of a set of strong-interaction nuclear radii using the photoproduction of neutral rho mesons. Analysis of 10^6 events from 13 complex nuclei yields the Woods-Saxon radii $R(A) = (1.12 \pm 0.02)A^{1/3}$ fm.

In recent years considerable theoretical[1] and experimental[2,3] effort has been made using nuclei as a tool to study elementary-particle physics. Attempts have been made to study the properties of elementary particles (stable and unstable) interacting with nuclear matter, such as the rho-nucleon cross section, the vector-dominance model, etc. A knowledge of the nuclear density distribution is essential in order to make a quantitative comparison between theory and experiment and to extract physical quantities from the data. To date, the nuclear density distributions have been assumed to be those determined from electron[4] or proton[5] scattering on complex nuclei. When using the electromagnetic nuclear radii, one assumes that the nuclear density distributions seen by strongly interacting particles are the same as those seen by the electron, an assumption which has not been justified. When using proton-scattering data to determine the radii, the problem of interference between the proton and the Coulomb field of the nuclei arises. Because of the importance of obtaining a reliable set of nuclear density distributions for strong interactions, we have performed an experiment specifically designed to measure strong-interaction radii with neutral particles.

This experiment measured the photoproduction of ρ^0 from nuclei,[2]

$$\gamma + A \rightarrow A + \rho^0 \rightarrow A + \pi^+ + \pi^-.$$

It was carried out at the 7.5-GeV DESY synchrotron using a bremsstrahlung beam and a magnetic spectrometer with a resolution of $\Delta m = \pm 15$ MeV/c^2, $\Delta p = \pm 150$ MeV/c, and $\Delta t_\perp = \pm 0.001$ (GeV/c)^2. We have investigated 13 elements: Be, C, Al, Ti, Cu, Ag, Cd, In, Ta, W, Au, Pb, and U. The measurements cover 20 intervals in the di-pion mass (m) from 400 to 1000 MeV/c^2, six intervals in the momentum (p) from 4.8 to 7.2 GeV/c, and 20 intervals in the transverse momentum transfer to the nucleus ($t_\perp$) from 0.0 to -0.04 (GeV/c)^2. These data form a four-dimensional matrix $d^2\sigma/d\Omega dm$ with dimensions $(A, m, p, t_\perp) = (13, 20, 6, 20)$ containing approximately 10^6 measured $\pi^+\pi^-$ events. A projection of 2% of the data (shown in Fig. 1 of the preceding Letter[2]) shows that the spectra are dominated by the ρ diffractively produced off the nucleus.

The slopes of the diffraction patterns measure directly the nuclear density distributions. For example, at $t \rightarrow 0$, the diffraction pattern behaves as e^{at} where a is a measure of the nuclear size. More specifically, we take the nuclear density distribution to be the Woods-Saxon form $\rho(r)=\rho_0/\{1+\exp[r-R(A)]/s\}$, where s is the skin-thickness parameter[5] taken to be 0.545 fm and $R(A)$ are the nuclear radii to be determined from this experiment.

To measure $R(A)$, the four-dimensional data matrix $d^2\sigma(A,m,p,t_\perp)/d\Omega dm$ was fitted with a theoretical function of the form

$$d^2\sigma/d\Omega dm=(1/\pi)p^2 2mR_n(m)(f_c+f_I)+f_{BG}(A,m,p,t_\perp). \quad (2)$$

The first term represents the main contribution from ρ photoproduction and the second term the contribution due to a nonresonant background;

$$f_c=(\sigma_E/\sigma)^2|2\pi f_0\int_0^\infty b\,db\int_{-\infty}^\infty dz\,J_0(b\sqrt{|t_\perp|})\exp(iz\sqrt{|t_\parallel|})\rho(z,b)^*,$$
$$\sigma_E=\sigma(1-\xi\eta\sigma)\exp\{-\tfrac{1}{2}\sigma_E(1-i\beta)\int_z^\infty\rho(z',b)dz'\}|^2\underset{t\to 0}{\propto}e^{at}. \quad (3)$$

Here f_c is the coherent production cross section[6] where the ρ meson, produced with an effective forward-production cross section $|f_0|^2$ on a single nucleon, is attenuated by $\exp[\frac{1}{2}\sigma_E(1-i\beta)\times\int_z^\infty\rho dz]$ as it leaves the nucleus. The factor $\rho(z,b)J_0(b\sqrt{|t_\perp|})$ comes from the nuclear shape, and the difference between initial and final mass produces a term $\exp(iz\sqrt{|t_\parallel|})$. The ρ-nucleon total cross section $\sigma=26.7\pm2.0$ mb comes from recent experiments.[2,7] The effective ρ-nucleon total cross section σ_E has taken into account second-order correlation effects between nucleons inside the nucleus in terms of the correlation parameters ξ and η. The ratio of the real part to the imaginary part of the scattering amplitude on a nucleon, β, was taken to be -0.2 from the analysis of γp total-cross-section measurements at 6.0 GeV.[8] For the incoherent production cross section f_I we used the formula of Trefil[9] which was found to reproduce proton-nucleus data at 19 GeV in our $t_\perp$ region. The incoherent contribution is largest for low A ($\approx$10%) and becomes negligible for $A>100$.

The following steps were taken to eliminate possible systematic effects: (1) To minimize the dependence on other variables in Eq. (2) ($f_I, f_{BG}, \beta, s, \sigma$), we selected the data in the region $|t_\perp|<0.01$ (GeV/c)^2, $4.8<p<7.2$ GeV/c, and $690<m<860$ MeV/c^2, where most of the pion pairs come from diffractive ρ production. More specifically, in the region defined above the maximum contribution of f_I is $\leq$10% for Be and C and is negligible for the heavy nuclei. A change of β of 50% changes $R(A)$ by <1%. A change of $\sigma_{\rho N}$ from 25 to 30 mb changes the results by $\leq$2%. For $A>27$, a change in $s=0.545$ fm by $\pm$10% changes the determination of $R(A)$ by $\leq$2%.

(2) To be independent of $R_n(m)$, the $\rho\to\pi\pi$ mass distribution (for which there is no unique theory), separate fits were made to the $t_\perp$ dependence of each of the six mass intervals between 690 and 870 MeV/c^2 for each element. Thus six independent determinations of the radius were obtained and the need for explicit assumptions for $R_n(m)$ was avoided. The first six rows of Table I list the results of the fits to the six mass bins for the case where the background was taken to be zero. As seen, for elements $A>27$, the radii determined from each of the individual mass bins are in good agreement with each other. This indicates that in the restricted kinematical region and for $A>27$ almost all the pairs are from rhos diffractively produced off the nucleus. The nonresonant background is either very small or is also diffractively produced off the nucleus. For light elements Be, C, and Al, the measured radii vary from one mass bin to another indicating that even within the restricted kinematical region above there still exists significant background. To ensure that our results are indeed insensitive to the background, checks were made by explicitly assuming various forms of background. We list four examples: (a) Background independent of p and $t_\perp$. For every element and for each mass bin we made a fit with one positive parameter corresponding to the background. (b) Background $f_{BG}(A,m,p,t_\perp)$ dependent on p and $t_\perp$. For every element and each mass bin, four positive parameters (for each element, 24 parameters) were fitted with each corresponding to the background in a small region of $(p,t_\perp)$ space. (c) A smooth background function $f_{BG}(A,m)$ which is a power series in m, and all mass bins fitted simultaneously with a mass distribution $R_1(m)=r(m)(m_\rho/m)^4$. The factor $r(m)$ is the relativistic p-wave resonance formula proposed by Jackson[10] and $(m_\rho/m)^4$ is the phenomenological Ross-Stodolsky factor[11] to account for the shape distortion and mass shift of the photoproduced rho spectrum. (d) A smooth background $f_{BG}(A,m)$ which is a power series in m, and all mass bins fitted simultaneously with a mass distribution $R_2(m)=r(m)+I(m)$. The function $I(m)$ repre-

Table I. Summary of radii. The first six rows are the results for individual mass-bin fits for zero background. The corresponding average radii are shown in row 7. Rows 8 through 11 show the results for cases (a), (b), (c), and (d) (see text). The last column in each case shows the results of fits to the scaling law $R = r_0 A^{1/3}$. The errors are statistical only. Our best values are shown in the last two rows where the errors also include systematic effects.

Fits	Be	C	Al	Ti	Cu	Ag	Cd	In	Ta	W	Au	Pb	U	r_0
705	1.59±0.37	2.49±0.27	3.14±0.24	3.49±0.24	4.56±0.16	5.03±0.13	5.31±0.16	5.32±0.16	6.42±0.15	6.34±0.17	6.36±0.16	6.58±0.13	6.85±0.11	1.10 ±0.01
735	1.80±0.35	1.70±0.27	3.00±0.22	3.76±0.19	4.39±0.15	5.24±0.12	5.12±0.13	5.56±0.12	6.34±0.11	6.24±0.14	6.53±0.12	6.62±0.11	6.88±0.09	1.11 ±0.01
BG=0 765	2.23±0.29	2.00±0.27	2.64±0.21	3.92±0.17	4.40±0.15	5.37±0.11	5.48±0.12	5.56±0.11	6.52±0.10	6.32±0.13	6.37±0.12	6.83±0.12	6.88±0.09	1.12 ±0.01
795	2.60±0.34	2.42±0.33	3.46±0.26	4.09±0.25	4.55±0.17	5.35±0.15	5.78±0.18	5.61±0.16	6.44±0.14	6.37±0.17	6.55±0.18	6.97±0.16	7.03±0.14	1.14 ±0.01
825	2.95±0.46	2.55±0.43	4.49±0.27	3.90±0.34	4.61±0.26	5.54±0.19	4.97±0.27	5.48±0.22	6.75±0.18	6.12±0.23	6.41±0.22	6.71±0.22	6.78±0.18	1.13 ±0.01
855	3.20±0.64	3.55±0.50	3.67±0.46	4.29±0.41	4.56±0.38	5.50±0.29	4.82±0.38	5.65±0.34	6.17±0.26	5.92±0.40	6.56±0.34	6.88±0.34	6.95±0.30	1.12 ±0.02
Average	2.24±0.15	2.27±0.13	3.28±0.10	3.86±0.10	4.48±0.07	5.29±0.06	5.35±0.07	5.53±0.06	6.45±0.06	6.28±0.07	6.45±0.07	6.72±0.06	6.89±0.05	1.119±0.004
a Average	2.86±0.25	2.91±0.22	4.08±0.24	4.07±0.17	4.71±0.12	5.30±0.07	5.48±0.13	5.57±0.08	6.50±0.09	6.36±0.09	6.52±0.09	6.81±0.08	6.93±0.06	1.132±0.005
b Average	2.47±0.49	2.44±0.50	3.73±0.42	4.06±0.20	4.55±0.16	5.30±0.09	5.54±0.14	5.60±0.10	6.50±0.09	6.42±0.09	6.55±0.11	6.84±0.08	6.98±0.06	1.136±0.005
c	2.59±0.16	2.54±0.13	3.32±0.12	3.94±0.25	4.62±0.09	5.58±0.08	5.55±0.10	5.58±0.11	6.42±0.12	6.44±0.12	6.74±0.11	6.76±0.11	7.04±0.09	1.147±0.006
d	2.40±0.16	2.42±0.14	3.24±0.11	3.96±0.11	4.56±0.05	5.53±0.10	5.50±0.08	5.55±0.08	6.44±0.17	6.42±0.12	6.72±0.15	6.83±0.09	7.06±0.09	1.140±0.006
Best Values: R(A)	2.35±0.26	2.50±0.23	3.37±0.16	3.94±0.10	4.55±0.11	5.35±0.09	5.40±0.14	5.56±0.25	6.50±0.15	6.30±0.12	6.45±0.27	6.82±0.20	6.90±0.14	1.12 ±0.02
rms	2.72±0.13	2.80±0.12	3.30±0.10	3.66±0.06	4.07±0.07	4.61±0.06	4.65±0.10	4.76±0.18	5.43±0.11	5.28±0.09	5.39±0.19	5.66±0.15	5.72±0.10	----------

sents the interference of the ρ amplitude with a part of the background where the nonresonant pairs are diffractively produced off the nucleus.[12] $R_2(m)$ represents another procedure to fit the spectrum with the mass shift and shape distortion accounted for by the interference term $I(m)$ whose magnitude is determined by the fit.

The results of (a), (b), (c), and (d) are listed in Table I in rows 8, 9, 10, and 11, respectively. For $A > 27$ they are consistent with each other and with the values determined from each individual mass bin with $f_{BG} = 0$.

Using the weighted average of the individual mass-bin values and taking into account the sensitivities to f_i, s, β, and σ, we list our best values in row 12 of Table I. These results are shown in Fig. 1. The last column in Table I lists the fits to the scaling law $R(A) = r_0 A^{1/3}$.

We can now calculate the rms radii corresponding to our best values for $R(A)$ as follows: $(R^2)_{rms} = 0.6R^2 + 1.4\pi^2 s^2$.[13] They are also listed in Table I.

Comments on the results.—(a) For heavy nuclei, $A > 27$, typical errors on $R(A)$ are $\approx 2\%$. These results, obtained from the weighted average of individual mass bins, are independent of mass distributions and, as discussed before, they are insensitive to parameters f_i, s, β, and σ and the background. (b) For light nuclei, $A < 27$, typical errors on $R(A)$ are $\approx 10\%$. This comes from the facts that (1) for light nuclei the fitted $R(A)$ are sensitive to background and skin thickness, and (2) Eq. (3) was derived from Glauber multiple-scattering theory for heavy nuclei; contributions from terms of order $1/A$, as well as individual nucleon form factors, have been ignored. (c) For all nuclei the fitted rms radii are insensitive to the skin-thickness parameters used, even for $A < 27$. This was verified in further fits using $s = 0.5$ and $s = 0.6$ fm. (d) Our results, obtained from neutral mesons, are free from complications of Coulomb interference terms. (e) From Eq. (3) it follows that the total hadronic cross sections can be expressed as

$$\sigma_T = 2\pi \int b\,db\{2 - 2\exp[-\tfrac{1}{2}\sigma_E T(b)]\cos[\tfrac{1}{2}\sigma_E T(b)\beta]\},$$
$$T(b) = \int_{-\infty}^{\infty} \rho(z, b)\,dz,$$
$$\sigma = (Z\sigma_p + \{A - Z\}\sigma_n)/A, \qquad (4)$$

where σ is the average nucleon-nucleon cross section in the nucleus. σ_p and σ_n are the proton and neutron total cross sections, respectively, for the incident hadrons. With our best value for $R(A)$ and with Eq. (4) we can evaluate σ_T and

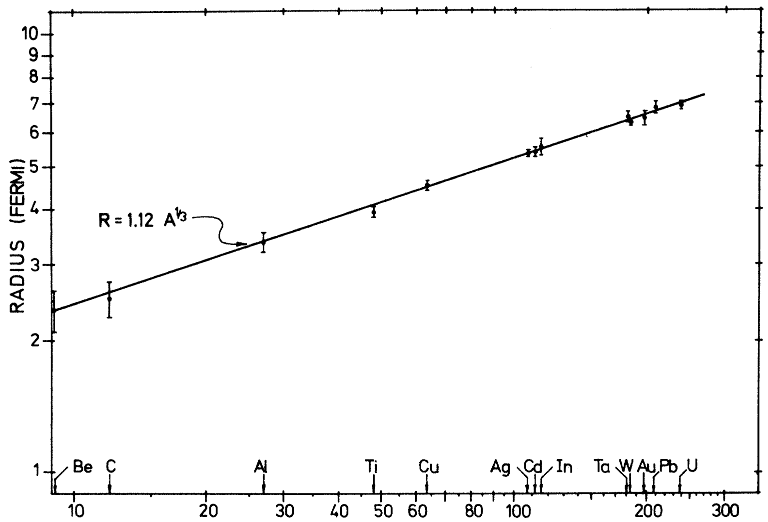

FIG. 1. Results on $R(A)$ and the best fit with $R=r_0 A^{1/3}$.

compare directly with measured data.[14] We list those cross sections where measurements of β at the same energy exist, and where the effects of possible inelastic shadowing[15] are small. This comparison is listed in Table II. The errors in the calculated σ_T include uncertainties in $R(A)$, β, and ξ (±0.2 fm). As seen, the calculated values agree with the experimental values from 5.7 to 20 GeV. This is an indication of the consistency of our radii and Eqs. (3) and (4). (f) Our result $R=(1.12\pm 0.02)A^{1/3}$ fm is compatible with the earlier determination by Glauber and Matthiae,[5] the latter being a 10% determination. They are to be compared with the electron scattering value[4] of $R(A)=1.07A^{1/3}$ fm.[16]

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Table II. Comparison of experimental total nucleon-nucleus cross sections with calculations of Eq. (4) using our radii. The uncertainty in the calculation Δ includes the errors in σ, β, ξ, and $R(A)$.

	20 GeV Proton, β = -.25±.08, $\sigma_{np}=\sigma_{pp}$ = 39.0 ± 0.5 mb				5.7 GeV Neutron, β = -.33±.08, σ_{pp} = 40.8±.4, σ_{np} = 42.5± .6				10 GeV Neutron, β = -.33±.08, σ_{np} = 39.5±.5, σ_{pp} = 38.9± .3			
	EXPT (mb)	THEORY ξ=0	THEORY ξ=-0.4fm	±Δ	EXPT (mb)	THEORY ξ=0	THEORY ξ=-0.4fm	±Δ	EXPT (mb)	THEORY ξ=0	THEORY ξ=-0.4fm	±Δ
Be	278 ± 4	276	290	11	301 ± 5	293	308	13	271 ± 6	282	297	12
C	335 ± 5	348	367	15	370 ± 6	369	390	18	340 ± 3	356	375	15
Al	687 ± 10	676	713	28	718 ± 13	711	752	31	683 ± 3	690	729	28
Cu	1360 ± 20	1312	1375	46	1410 ± 30	1369	1436	49	1364 ± 14	1338	1403	47
Cd	-	1953	2032	70	2120 ± 30	2023	2104	76	-	1988	2067	72
W	-	2729	2819	83	2970 ± 70	2808	2899	85	-	2770	2859	83
Pb	3290 ±100	3103	3203	127	3240 ± 50	3192	3294	135	3146 ± 35	3150	3249	130
U	-	3278	3374	103	3620 ± 60	3364	3460	107	-	3323	3418	104

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$$r(m)=\frac{1}{\pi}\frac{m_\rho\Gamma(m)}{(m_\rho^2-m^2)^2+m_\rho^2\Gamma^2(m)},$$

$$\Gamma(m)=\frac{m_\rho}{m}\left\{\frac{(m/2)^2-m_\pi^2}{(m_\rho/2)^2-m_\pi^2}\right\}^{3/2}\Gamma_0.$$

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[15]We have also calculated the total absorptive π^-, K^-, $\bar{p}$ cross sections on the nucleus at 40 GeV/c. Our results for $A>27$ are $\approx 6\,\%$ higher than the values of J. Allaby et al. (We thank Professor A. N. Diddens for communications.) This difference can perhaps be explained by inelastic shadowing effects at extremely high energies. (See J. Pumplin and M. Ross, Phys. Rev. Letters 21, 1778 (1968); G. Alberi and L. Bertocchi, Nuovo Cimento 61A, 203 (1969).

[16]Using our radii, we have reanalyzed the preliminary data of φ production on nuclei [U. Becker et al., DESY Report No. F31/2, 1968 (unpublished).] We obtain these preliminary results: $\beta=0$, $\sigma_{\varphi N}=16.2\pm3.0$ mb; $\beta=-0.2$, $\sigma_{\varphi N}=11.3\pm2.5$ mb; $\beta=+0.2$, $\sigma_{\varphi N}=20\pm4.0$ mb, all with $\xi=0$. We stress the extreme preliminary nature of these results. A 20-element, high-statistics experiment, including measurements of β, $R(A)$, ξ, f_I, and background, has not yet been finished. The difference of $\sigma_{\varphi N}$ by one standard deviation from the old value is due to the difference of radii used in the analysis.

ERRATUM

TOTAL PHOTOABSORPTION CROSS SECTIONS UP TO 18 GeV AND THE NATURE OF PHOTON INTERACTIONS. D. O. Caldwell, V. B. Elings, W. P. Hesse, G. E. Jahn, R. J. Morrison, F. V. Murphy, and D. E. Yount [Phys. Rev. Letters 23, 1256 (1969)].

On page 1258, Eq. (1), the denominator in the right-hand side should read $d\sigma(\gamma p\to\rho P)/d\sigma_{t=0}$. On page 1259, left column, lines 9 and 33 read "$\cdots\rho$-nucleon coupling$\cdots$" and should be changed to read "$\cdots\gamma$-ρ coupling$\cdots$".