Test of Charge Symmetry in π^+ and π^- Elastic Scattering on Tritium and ^{3}He

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Elastic scattering of 180-MeV π^+ and π^- on ^{3}He and tritium has been measured from θ_π(c.m.) = 44° to 96°. The superratio

$$R \equiv [d\sigma(\pi^+ + {}^3\mathrm{H})/d\sigma(\pi^- + {}^3\mathrm{He})]/[d\sigma(\pi^+ + {}^3\mathrm{He})/d\sigma(\pi^- + {}^3\mathrm{H})]$$

is found to vary with angle reaching a maximum of 1.31 ± 0.09 at $\theta_\pi = 65°$. The direct Coulomb effects do not account for the observed differences of R from 1.0 which is the expected value on the basis of charge symmetry.

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We present here the results of a novel test of the validity of charge symmetry (CS) at intermediate energy based on measurements of the superratio, R, which we have defined as the ratio of ratios of two pairs of charge-conjugate reactions,

$$R \equiv \frac{d\sigma(\pi^+ + {}^3\mathrm{H})/d\sigma(\pi^- + {}^3\mathrm{He})}{d\sigma(\pi^+ + {}^3\mathrm{He})/d\sigma(\pi^- + {}^3\mathrm{H})}.$$

If CS is valid, $R = 1$ at each angle at all energies after corrections have been applied for electromagnetic effects. In this experiment, the superratio is obtained from four relative yields,

$$R = \frac{Y(\pi^+ + {}^3\mathrm{H})}{Y(\pi^+ + {}^3\mathrm{He})}\,\frac{Y(\pi^- + {}^3\mathrm{H})}{Y(\pi^- + {}^3\mathrm{He})},$$

where Y is the yield per (arbitrary) beam monitor, corrected for background from the target walls. Precise, relative beam monitoring was accomplished by use of two ionization chambers; the monitoring was carefully checked every run by measuring π-Fe scattering from the walls of each target. The measurement of R thus does not depend on the absolute calibration of the incident pion beam flux or the spectrometer acceptance. Another advantage of using R to test CS is that several corrections for the Coulomb effects cancel in first order.

The experiment was performed at the Los Alamos Meson Physics Facility (LAMPF). We employed five identical gas target cells; each was a 12-cm-diam stainless-steel sphere of 0.06-cm wall thickness equipped with a special fill tube that was welded shut after the sphere was filled. The spheres were copper clad and covered with a gold flash to insure that the diffusion of tritium out of the target during the experiment was completely negligible. The first sphere was filled with tritium (30 000 Ci) and deuterium with partial pressures of 1.0 MPa (10 atm) and 0.3 MPa, respectively. The second sphere contained ^{3}He at 1.0 MPa and deuterium at 0.3 MPa. The admixture of the dueterium in both targets enabled us to measure π-d scattering simultaneously with the π-^{3}He and π-^{3}H scattering. At θ_π = 40°, 50°, and 60° these π-d measurements were sufficiently precise to provide an independent check on the stability of the beam monitor and the detection system. The three remaining spheres were used for calibration purposes: The first contained hydrogen at 1.3 MPa, the second deuterium at 1.3 MPa, and the third was an evacuated sphere.

The EPICS spectrometer was used to measure the elastic scattering of pions at θ_π(lab) = 40° to 90° in steps of 10° at T_π = 180 MeV. At each angle we measured successively the π^+ yield from the tritium, ^{3}He, and hydrogen targets with the spectrometer tuned for pion-tritium elastic-scattering kinematics, yielding $\rho_1 = Y(\pi^+ + {}^3\mathrm{H} \to \pi^+ + {}^3\mathrm{H})/Y(\pi^+ + {}^3\mathrm{He} \to \pi^+ + {}^3\mathrm{He})$; the background was measured with use of the hydrogen target. The measurement of ρ_1 was followed immediately by data collection on the hydrogen and the evacuated targets

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with the spectrometer tuned for π-p kinematics to obtain a measure of the pion flux and spectrometer acceptance for use in the measurements of the "simple" ratios, r_1 and r_2, which are discussed below. This sequence was repeated for incident π^- to measure $\rho_2 = Y(\pi^- + {}^3\mathrm{H} \to \pi^- + {}^3\mathrm{H})/Y(\pi^- + {}^3\mathrm{He} \to \pi^- + {}^3\mathrm{He})$. For all our measurements the spectrometer acceptance, as defined by software cuts, remained the same.

The superratio is obtained as $R = \rho_1 \rho_2$; the results are shown in Fig. 1(a) where the error bars indicate only statistical uncertainties. The sole important systematic error comes from the uncertainty in the ratio of the pressures of the tritium and ^{3}He gases in the targets. The partial pressures of all target constituents were measured at the time of filling. At the end of the experiment the pressure in each cell was measured again with use of a special device to open the sealed containers without loss of gas, followed by a mass spectroscopic analysis of the target gases. The uncertainty in the ^{3}H-to-^{3}He gas-pressure ratio based on the extremes in the pressure measurements is $+1.5\%$, -3%, giving a $+3\%$, -6% uncertainty in R. The dashed lines in Fig. 1(a) at $R = 1.06$ and 0.97 represent this systematic error which inversely affects the expectations of 1.0 and scales all R's. The superratio deviates substantially from 1.0. The largest effect occurs at $\theta_\pi(\mathrm{c.m.}) = 65°$ where $R = 1.31 \pm 0.09$.

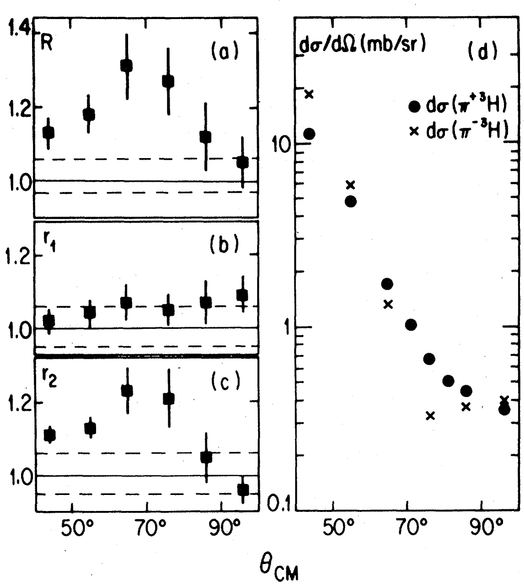

FIG. 1. (a) Superratio, R, of $\pi^\pm$ elastic scattering on ^{3}H and ^{3}He at $T_\pi = 180$ MeV. $R \equiv d\sigma(\pi^- + {}^3\mathrm{H})\,d\sigma(\pi^+ + {}^3\mathrm{H})/d\sigma(\pi^- + {}^3\mathrm{He})\,d\sigma(\pi^+ + {}^3\mathrm{He})$. (b) Simple ratio, r_1, at $T_\pi = 180$ MeV, $r_1 \equiv d\sigma(\pi^+ + {}^3\mathrm{H})/d\sigma(\pi^- + {}^3\mathrm{He})$. (c) Simple ratio, r_2, at $T_\pi = 180$ MeV, $r_2 \equiv d\sigma(\pi^- + {}^3\mathrm{H})/d\sigma(\pi^+ + {}^3\mathrm{He})$. (d) Differential cross section vs $\theta_\pi(\mathrm{c.m.})$ for π^+ and π^- elastic scattering on ^{3}H at $T_\pi = 180$ MeV.

There are two other interesting ratios which can be determined in our experiment. They are the "simple" ratios, r_1 and r_2, defined as

$$r_1 \equiv d\sigma(\pi^+ + {}^3\mathrm{H})/d\sigma(\pi^- + {}^3\mathrm{He}),$$

$$r_2 \equiv d\sigma(\pi^- + {}^3\mathrm{H})/d\sigma(\pi^+ + {}^3\mathrm{He}).$$

If CS is valid $r_1 = r_2 = 1$. The determination of these ratios requires the absolute calibrations of the EPICS beams and the acceptance of the EPICS spectrometer. We determined the ratios r_1 and r_2 from the $\pi^\pm$ elastic-scattering yields from tritium, ^{3}He, and hydrogen and the π^+p/π^-p elastic-scattering cross-section ratio as obtained from a recent πN partial-wave analysis (PWA)[1]:

$$r_1 = \frac{Y(\pi^+ + {}^3\mathrm{H})}{Y(\pi^- + {}^3\mathrm{He})}\,\frac{Y(\pi^- p)}{Y(\pi^+ p)}\left[\frac{d\sigma(\pi^+ p)}{d\sigma(\pi^- p)}\right]_{\mathrm{PWA}},$$

$$r_2 = \frac{Y(\pi^- + {}^3\mathrm{H})}{Y(\pi^+ + {}^3\mathrm{He})}\,\frac{Y(\pi^+ p)}{Y(\pi^- p)}\left[\frac{d\sigma(\pi^- p)}{d\sigma(\pi^+ p)}\right]_{\mathrm{PWA}}.$$

We have taken the ratios for $[d\sigma(\pi^+ p)/d\sigma(\pi^- p)]_{\mathrm{PWA}}$ from the Karlsruhe-Helsinki[1] partial-wave analysis, which at our energy agree to within $\pm 3\%$ with the Virginia Polytechnic Institute[2] PWA. The results for the ratios r_1 and r_2 are shown in Figs. 1(b) and 1(c). The dashed lines near $r = 1.0$ indicate the systematic error of -5%, $+6\%$ resulting from uncertainties of 3% in $[d\sigma(\pi^+ p)/d\sigma(\pi^- p)]_{\mathrm{PWA}}$, 4% in $Y(\pi^+ p \to \pi^+ p)/Y(\pi^- p \to \pi^- p)$, and $+1.5\%$, -3% in the ratio of the tritium to ^{3}He gas pressures. Note that a change in the π^+/π^- normalization would affect r_1 and r_2 in opposite ways.

External radiation of soft photons has been evaluated with the external-emission-dominance approximation[3] and found to have less than 1% effect on the above ratios. The effect of the pure Coulomb interaction, $d\sigma_C = |A_C|^2$, where A_C is the Coulomb amplitude,[4,5] is less than 1% at our scattering angles. The Coulomb-nuclear interference term is $2A_C A_N \cos\varphi$, where A_N is the nuclear-scattering amplitude and φ is the relative phase between A_C and A_N. At $T_\pi = 180$ MeV φ is near 90°, making the interference term small.[5] Even in the implausible case that φ is not close to 90°, the maximum effect is still less than 5% in r_1 and r_2 and cancels in first order in R. The effect of the Coulomb energy shift, ΔE_C, also cancels in first order in R but not in r_1 and r_2. There is some uncertainty about the magnitude of ΔE_C: Masterson *et al.*[6] use 0.75 MeV for πd scattering at $T_\pi = 143$ MeV; Ingram *et al.*[7] quote 4 MeV for ^{16}O and 7 MeV for ^{40}Ca, which implies a shift in the position of the first minimum in $\pi + {}^{40}$Ca elastic scattering at $T_\pi = 163$ MeV of 3°, but only 1.5° has been observed.[7] We estimate that the Coulomb energy shift increases r_1 by 3% and decreases r_2 by a similar amount. The Coulomb distortion of the nuclear potential is small[8]; an estimate of the effect by Gibbs[9] indicates that it has the wrong sign to explain our measured ratios. We summarize the evaluation of the CS-violating electromagnetic interactions as follows. The Coulomb effects are less than 7%, too small to account for the observed deviations of the ratios R, r_1, and r_2 from 1.0. The smallness of the Coulomb corrrections in this experiment is due in part to our choice of incident energy (at the peak of the Δ resonance) and scattering angles ($\geq 40°$). In a recent $\pi^\pm + {}^{12}$C scattering experiment[10] at $T_\pi = 180$ MeV, the π^+-to-π^- ratio was measured to be close to one, about 1.1 ± 0.1, except in very forward directions and in the diffraction dip. This corroborates our evaluation of the size of the Coulomb corrections which are much larger in ^{12}C because of its greater Z.

To place in perspective the magnitude of the observed deviation of r_2 from one we have calculated the differences in cross sections between the CS-related reactions measured in this experiment, $d\sigma(\pi^+ + {}^3\mathrm{H}) - d\sigma(\pi^- + {}^3\mathrm{He})$ and $d\sigma(\pi^- + {}^3\mathrm{H}) - d\sigma(\pi^+ + {}^3\mathrm{He})$. The results are shown in Table I together with related data, namely $d\sigma(\pi^+ d) - d\sigma(\pi^- d)$ measured at $T_\pi = 143$ MeV,[6] and $d\sigma(\pi^+ + {}^4\mathrm{He}) - d\sigma(\pi^- + {}^4\mathrm{He})$ measured at $T_\pi = 200$ MeV.[11] In each case in Table I we have listed both the statistical and the systematic uncertainties. For the deuterium experiment we use $\pm 3\%$ for the systematic uncertainty, based on the variation between the πp cross sections given by the πp partial-wave analyses,[1,2] and for the ^{4}He experiment we use $\pm 10\%$.[11] At each angle except 86° and 96° the difference $d\sigma(\pi^- + {}^3\mathrm{H}) - d\sigma(\pi^+ + {}^3\mathrm{He})$ far exceeds the differences measured with a deuterium or ^{4}He target; the latter two differences are consistent with zero within error. The fact that $d\sigma(\pi^- + {}^3\mathrm{H}) - d\sigma(\pi^+ + {}^3\mathrm{He})$ is substantially larger than $d\sigma(\pi^+ d) - d\sigma(\pi^- d)$ or $d\sigma(\pi^+ + {}^4\mathrm{He}) - d\sigma(\pi^- + {}^4\mathrm{He})$ implies, barring unforeseen cancellations, that the deviation of R from 1.0 is not due mainly to the possible inequality, $d\sigma(\pi^+ p) \neq d\sigma(\pi^- n)$, which would be a direct violation of CS. Rather, it indicates that the origin of $R \neq 1.0$ stems from a difference in the hadronic properties of ^{3}H and ^{3}He. This is not the first time that the trinucleon system has revealed CS-breaking properties: The binding-energy difference between ^{3}H and ^{3}He is larger than can be accounted for by electromagnetic interactions[12] and the excess is attributed to CS-breaking interactions.

Figure 1(a) shows a strong angular dependence of the superratio: $R = 1.13 \pm 0.05$ at $\theta_{\mathrm{c.m.}} = 44°$, increasing to $R = 1.31 \pm 0.09$ at $\theta_{\mathrm{c.m.}} = 65°$ and decreasing to $R = 1.05 \pm 0.07$ at $\theta_{\mathrm{c.m.}} = 96°$. There are no systematic errors in the determination of the *variation* of R with θ as it is independent of all calibrations, including the ratio of the ^{3}H and ^{3}He gas pressures. That is, a change in the ratio of the gas pressures would shift all points in Fig. 1(a) an equal amount up or down; the variation of R with angle would remain. The variation in R is not associated with a steep dip in the cross section which is shown in Fig. 1(d); this is in contrast to the case for $\pi^\pm + {}^{12}$C scattering.[10] As most of the Coulomb corrections cancel in R, the observed variation of R with θ is a compelling experimental demonstration that ^{3}H and ^{3}He have different hadronic properties.

The angular dependence of R is not surprising; consider the single-scattering approximation[13] in which the pion-tritium elastic-scattering ampli-

TABLE I. Differences in differential cross sections related by charge symmetry. Units are millibarns per steradian; both the statistical and systematic uncertainties are listed in each case.

$\theta_{\mathrm{c.m.}}$	$\pi^+ + {}^3\mathrm{H} - \pi^- + {}^3\mathrm{He}$	$\pi^- + {}^3\mathrm{H} - \pi^+ + {}^3\mathrm{He}$	$\pi^+ d - \pi^- d$	$\pi^+ + {}^4\mathrm{He} - \pi^- + {}^4\mathrm{He}$
44°	$+0.2 \pm 0.3 \pm 0.6$	$+2.1 \pm 0.3 \mp 0.9$	$-0.2 \pm 0.3 \pm 0.2$	$+0.2 \pm 0.5 \pm 1.9$
55°	$+0.2 \pm 0.2 \pm 0.3$	$+0.6 \pm 0.2 \mp 0.3$	$-0.1 \pm 0.2 \pm 0.14$	$+0.2 \pm 0.1 \pm 0.5$
65°	$+0.09 \pm 0.10 \pm 0.15$	$+0.28 \pm 0.07 \mp 0.15$	$-0.1 \pm 0.1 \pm 0.07$	$+0.07 \pm 0.04 \pm 0.09$
76°	$+0.04 \pm 0.03 \pm 0.04$	$+0.05 \pm 0.02 \mp 0.02$	$-0.03 \pm 0.05 \pm 0.05$	$-0.01 \pm 0.01 \pm 0.02$
86°	$+0.03 \pm 0.01 \pm 0.03$	$+0.02 \pm 0.03 \mp 0.02$	$-0.07 \pm 0.04 \pm 0.04$	$-0.01 \pm 0.01 \pm 0.02$
96°	$+0.03 \pm 0.01 \pm 0.02$	$-0.01 \pm 0.02 \mp 0.02$	$-0.06 \pm 0.04 \pm 0.03$	...
T_π	180 MeV	180 MeV	143 MeV	200 MeV

tude $A(\pi + {}^3\mathrm{H})$ is given by

$$A(\pi + {}^3\mathrm{H}) = A_0(\pi p)F_p({}^3\mathrm{H}) + A_0(\pi n)F_n({}^3\mathrm{H}) + A_F(\pi p)F_p({}^3\mathrm{H});$$

$A_0(\pi N)$ is the non-spin-flip πN scattering amplitude; at our energy $|A_0(\pi N)|^2$ is roughly proportional to $4\cos^2\theta$. $A_F(\pi p)$ is the spin-flip amplitude and $|A_F(\pi N)|^2$ varies approximately as $\sin^2\theta$. $F_p({}^3\mathrm{H})$ $[F_n({}^3\mathrm{H})]$ is the proton [neutron] form factor in ^{3}H. We have taken the double-neutron–spin-flip amplitude to be zero and equated the spin form factor of ^{3}H with the proton form factor. The variation of R with θ is a consequence of the different angular distributions of the non-spin-flip and the spin-flip parts of the πN scattering cross section. The variation of the ^{3}H and ^{3}He form factors with t does not generate the variation of R as shown in Fig. 1(a), as the dip in the ^{3}He and ^{3}H form factors occurs at much larger t than the range in this experiment.

The difference between the neutron form factor of ^{3}H and the proton form factor of ^{3}He could be the result of a CS-violating three-nucleon force[14] and/or a difference in the coupling constants: $f(pp\pi^0) \neq f(nn\pi^0)$. Such a difference can come from the inequality of the u- and d-quark masses as considered, e.g., by Thomas *et al.*[15] and it would be a genuine violation of nuclear CS. This must be distinguished from the difference due to the Coulomb repulsion of the two protons in ^{3}He. Using coordinate-space Faddeev techniques, Payne *et al.*[16] have calculated that the rms radius of ^{4}He increases only by about 0.04 fm when a Coulomb-distorted wave function is used instead of a pure nuclear wave function. These authors have also evaluated the Coulomb-induced $I = \frac{3}{2}$ wave-function components and found them to be very small, eliminating isospin mixing in the trinucleon system as the source of $R \neq 1.0$.

In summary, we find a large departure of R from the expectation $R = 1.0$ based on charge symmetry; very significant is the strong variation of R with scattering angle completely free of systematic errors. A possible explanation may be based on differences in the matter and spin form factors of ^{3}H and ^{3}He. The source of such differences is not yet determined; it can be a "trivial" violation of CS due to Coulomb repulsion of the protons in ^{3}He, or more likely due to a difference in coupling constants, implying a genuine CS violation. To settle this question, more measurements of R at different energies and other angles, as well as better calculations of the Coulomb effects in the trinucleon system, are needed.

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