Measurement of Isospin Mixing in ^{4}He and Its Implications for Charge-Symmetry Breaking

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π-^{4}He inelastic cross sections have been measured at $T_\pi = 180$ MeV. In the region of the $J^\pi = 1^-$ states ($E_x \simeq 23$ to 30 MeV) the π^+/π^- cross-section ratio R_π was found to be 1.05 ± 0.08 at $\theta_{\rm lab} = 30°$. Such a small deviation from 1.0 implies that isospin mixing between the $T = 0$ and $T = 1$ states in ^{4}He is quite weak, in striking contrast to the strong isospin mixing deduced from the large ratio of photonucleon cross sections, $R_\gamma = \sigma(\gamma,p)/\sigma(\gamma,n) \simeq 1.7$. Thus the conclusion drawn from the photonucleon work, that there is a large charge-symmetry-breaking nuclear force in ^{4}He, needs to be reexamined.

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A recent critical review[1] of the numerous measurements[2] of the (γ,p) and (γ,n) photonucleon cross sections on ^{4}He presents a cross-section ratio $R_\gamma \equiv \sigma(\gamma,p)/\sigma(\gamma,n)$ between 1.5 and 1.9 at excitation energies E_x below 30 MeV. Measurements of the cross sections for the proton[3] and neutron[4] capture reactions, ^{3}H(p,γ) and ^{3}He(n,γ), confirm the (γ,p) and (γ,n) results. The experimental value of $R_\gamma \sim 1.7$ is in striking contrast to the value of 1.0 which would be expected if the proton-proton and neutron-neutron forces were equal so that the excited states of ^{4}He would be states of good isospin T. The γ radiation in the photonucleon reactions involves predominantly electric dipole radiation ($E1$). Thus the large value of R_γ may be due to isospin mixing between the $J^\pi = 1^-$, $T = 0$, and $T = 1$ states in ^{4}He (Ref. 1). Because Coulomb effects can cause R_γ to be only slightly larger ($\simeq 10\%$) than 1.0 at 2 to 3 MeV above the $p + {}^3$H threshold (19.82 MeV),[5-7] the authors of Ref. 1 suggested the presence of a large charge-symmetry-breaking (CSB) nuclear force in ^{4}He which would cause strong isospin mixing between the 1^- states. An analysis[1] of the photonucleon data with the two-level isospin-mixing formula of Barker and Mann[8] yielded a CSB matrix element $\langle T = 1 | H_{\rm CSB} | T = 0 \rangle$ of nearly 500 keV, i.e., much larger than the value expected from the Coulomb force ($\simeq 100$ to 150 keV). An even larger matrix element ($\simeq 2.5$ MeV) was extracted[9] in a calculation which included $3\hbar\omega$ excitations. The existence of large CSB forces such as invoked in Refs. 1 and 9 would fundamentally change our present understanding of the nuclear force.

It has been shown[10,11] that CSB forces of the magnitude required to reproduce the experimental value of R_γ generate large differences between the polarization (P) and the analyzing power (A) in the reaction ^{3}H$(p,n)^3$He. Experimentally,[12,13] however, only small differences have been observed between A and P, in very good agreement with theoretical predictions[11] which include only the Coulomb interaction as a CSB force. It is therefore necessary to measure the degree of isospin mixing by another method.

Inelastic scattering of π^+ and π^- near the [3,3] resonance has been established[14,15] to be a reliable method for the determination of isospin mixing. For the $J^\pi = 1^+$ isospin doublet in ^{12}C (12.71 MeV, $T=0$, and 15.11 MeV, $T=1$) the CSB matrix element has been found[14] to be $\simeq 150$ keV. This result agrees very well with electromagnetic measurements and theoretical expectations for isospin mixing due to the Coulomb force. Thus, in order to obtain an independent determination of isospin mixing in ^{4}He, we have measured differential cross sections $\sigma(\pi^+)$ and $\sigma(\pi^-)$ for inelastic pion scattering from ^{4}He at $T_\pi = 180$ MeV.

The energetic pion channel and spectrometer system (EPICS)[16] at the Los Alamos Meson Physics Facility (LAMPF) was used to measure spectra at $\theta_{\rm lab} = 20°$, 30°, and 40° up to $E_x = 45$ MeV excitation energy. The target was helium gas, cooled to a temperature $T \simeq 17$ K at a pressure $P \simeq 2$ atm. The target container was a cylinder of 0.23-m height and 0.127-m diameter with nickel walls of 40-mg/cm^2 areal density. The areal density of the cooled helium was $\simeq 65$ mg/cm^2. The energy resolution was $\simeq 500$ keV (FWHM) and the angular acceptance was 3°.

The absolute differential cross sections were determined by a measurement of π-hydrogen yields, with methane as a target, and normalizing the yields to $\pi + p$ cross sections, calculated from the phase shifts of Thiessen and Sobottka.[17] We also measured spectra from the empty target container to determine the background contribution from the target can. For $\theta_{\rm lab} = 30°$ the background amounted to about 15% of the total counts.

The experimental spectra at $\theta_{\rm lab} = 30°$ (after background subtraction) were converted to differential cross sections $\sigma(\pi) \equiv d^2\sigma/d\Omega\, dE$. The results are shown in Fig. 1 for $E_x \leqslant 36$ MeV. The error bars are due to statistics and the uncertainties in background subtraction only. Uncertainties in target thicknesses, pion decay fractions, wire-chamber efficiencies, computer live time, spectrometer acceptance, beam monitoring, and predicted $\pi + p$ cross sections lead to a conservative estimate of $\pm 15\%$ uncertainty in the absolute differential cross sections.

In contrast to the photonucleon reactions, which are dominated by electric dipole absorption, inelastic scattering by pions excites all the states in ^{4}He, except for the $J^\pi = 0^-$ state. All excited states of ^{4}He are particle unbound. Thus the spectra show a broad continuum of states above threshold ($\simeq 20$ MeV). Nevertheless, the first excited 0^+ state at 20.5 MeV and the 2^- state near 22 MeV are clearly visible in Fig. 1. As indicated by the theoretical curves (to be discussed below), the 1^- continuum peaks near 25 MeV. At

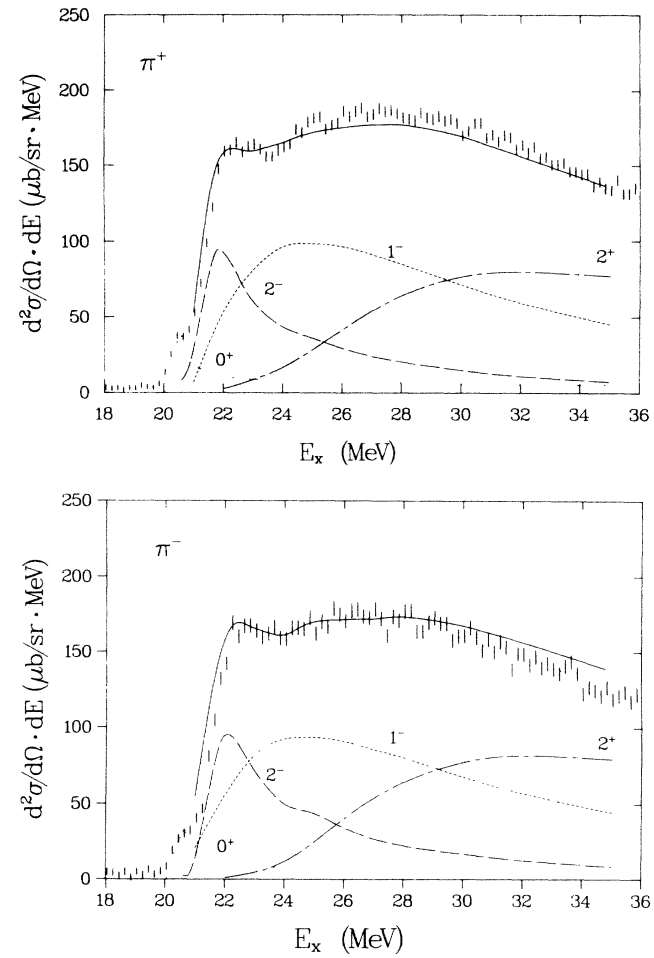

FIG. 1. Spectra of ^{4}He$(\pi^+,\pi^{+\prime})$ and ^{4}He$(\pi^-,\pi^{-\prime})$ at $\theta_{\rm lab} = 30°$ and $T_\pi = 180$ MeV. The curves are the results of distorted-wave impulse-approximation (DWIA) calculations as described in the text. The DWIA curves for the 2^- states have been multiplied by a factor of 1.35 for both π^+ and π^- in order to fit the data better.

$E_x > 31$ MeV, the 2^+ continuum makes the largest contribution to the cross sections.

Our principal result is contained in Fig. 2 which shows near unity values for the cross-section ratio $R_\pi = \sigma(\pi^+)/\sigma(\pi^-)$ at all E_x beyond the threshold region ($E_x \geqslant 22$ MeV). Only the (E_x-dependent) statistical and background subtraction errors are shown for R_π which was averaged over 400-keV intervals. Several sources of absolute cross-section uncertainty, such as target thicknesses and spectrometer acceptance, do not contribute to the uncertainty in R_π. The other sources of (mostly E_x-independent) error contribute a systematic uncertainty of $\pm 8\%$. Averaged over the region of the 1^- states ($E_x = 23$ to 30 MeV), where $R_\gamma \simeq 1.7 \pm 0.2$, we find $R_\pi = 1.05 \pm 0.08$ at $\theta_{\rm lab} = 30°$. The error of ± 0.08 is dominated by the systematic uncertainty in R_π. Values of R_π near

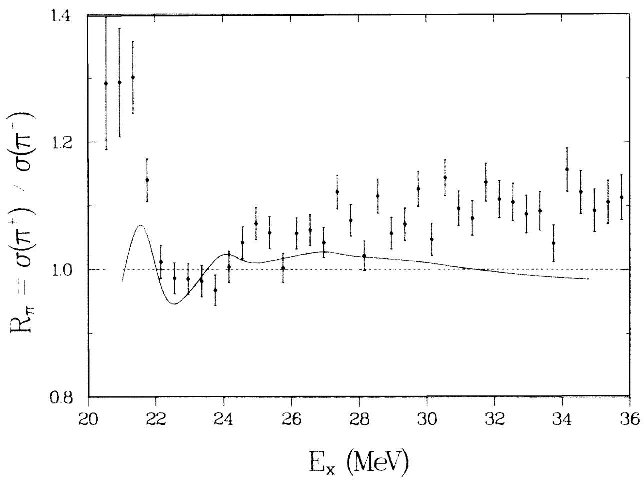

FIG. 2. R_π as a function of excitation energy E_x at $\theta_{lab} = 30°$ and $T_\pi = 180$ MeV. Solid line: DWIA prediction.

threshold are larger than 1.0 because the separation threshold for protons (19.82 MeV) is lower than that for neutrons (20.58 MeV). At 20° and 40° the values of R_π in the region of the 1^- states are also consistent with 1.0. At 20° the background was larger than at the other angles which made a realistic estimate of the error too difficult. At 40° the 2^- states are more strongly excited than at 30° where the differential cross sections for the 1^- states are expected to peak. Thus the data at 30° provide the most precise determination of R_π in the region of the 1^- states.

In Ref. 1 the large value of R_γ was attributed to isospin mixing between $T=0$ and $T=1$, $J^\pi = 1^-$ states. Application of the two-state mixing formalism of Ref. 8 led to a ratio of the $T=0$ reaction amplitude (a_0) to the $T=1$ amplitude (a_1) of $|a_0/a_1| = 0.13$ for the transition to an isospin-mixed state near 25 MeV, which was presumed to be predominantly a $T=1$ state. Within the two-level mixing model this value of $|a_0/a_1|$ represents a $T=0$ admixture in the $T=1$ state of amplitude $|\beta| = 0.13$. Such a large admixture should be easily detectable in inelastic pion scattering because of the isospin dependence of the pion-nucleon interaction.

At pion energies near the [3,3] resonance the pion-nucleon interaction enhances the $T=0$ parts of the transition density amplitudes over the $T=1$ parts by a factor of $+2$ for π^- and a factor of -2 for π^+. Thus in the plane-wave Born approximation the cross-section ratio would be $R_\pi = [(\alpha - 2\beta)/(\alpha + 2\beta)]^2 = 2.9$ for a $T=1$ state with a $T=0$ admixture of amplitude $\beta = -0.13$, where $\alpha = (1-\beta^2)^{1/2}$. The observed value of R_π shows that isospin mixing is much smaller, i.e., β is of the order of 1% if the two-level mixing formalism describes this case.

As pointed out in Refs. 1 and 9, the $T=0$, $S=0$, 1^- state in a $1\hbar\omega$ model space is entirely due to spurious center-of-mass motion. Shell-model calculations generate higher-order nonspurious $T=0$, $S=0$ states but mixing with the $T=1$ states is much more complicated than in two-level[8,9] mixing of isolated states. Since the ^{4}He states are all very broad and overlap, isospin mixing changes continuously with E_x as do the contributions from $S=1$ states. For equal spectroscopic amplitudes the $S=1$ contributions to the cross sections are smaller than the $S=0$ contributions because of the relatively weaker π-nucleon spin-orbit interaction. However, they are not negligible as for photonucleon reactions.

The conclusion of small isospin mixing in ^{4}He is fully supported by distorted-wave calculations using the wave functions from the recoil-corrected continuum shell model (RCCSM).[18] The Coulomb force is the only CSB force applied in the RCCSM calculations and the resulting wave functions provide very good agreement with low-energy nucleon scattering data. These include differential cross sections ($d\sigma/d\Omega$) and A for elastic scattering of neutrons from ^{3}He and protons from ^{3}H, as well as $d\sigma/d\Omega$, A, and P for the reaction ^{3}H$(p,n)^3$He.[12,13] They also reproduce the ^{4}He(γ,p) absolute cross section and the shapes of the angular distributions for the capture reactions ^{3}He(n,γ) and ^{3}H(p,γ).[19–21] However, they predict $R_\gamma \simeq 1.0$. We note that, by imposing continuum boundary conditions on the excited nucleons, the RCCSM reaction calculations include the quasielastic process as well as the scattering through resonance states.

The procedure followed to calculate the pion differential cross sections $d^2\sigma/d\Omega\, dE_x$ by the distorted-wave impulse approximation has been discussed by Halderson *et al.*[22] The transition densities were calculated with a modified version of ALLWORLD[23] and entered into the program MSUDWPI[24] to generate the $d^2\sigma/d\Omega\, dE_x$ for E_x between 20 and 35 MeV. For the distorted waves we employed the wave equation of Stricker, McManus, and Carr.[25] The optical potential parameters were determined from the free π-nucleon phase shifts evaluated 20 MeV below the incident pion energy in the spirit of Cottingame and Holtkamp.[26] The nuclear density was of Gaussian form, $\exp(-r^2/a^2)$, with $a = 1.3$ fm. The DWIA cross sections were found to be quite sensitive to the distorting potentials. However, the predicted cross-section ratio R_π above 23 MeV is always near 1.0, ranging from about 1.0 to 1.1.

The theoretical predictions for the cross sections shown in Fig. 1 were obtained with an energy-dependent optical potential in the outgoing channel. They are presented for the individual multipolarities $(0^+, 2^-, 1^-, 2^+)$ as well as for the sum (solid line). The π^+ and π^- predictions for the 2^- states were renormalized by a factor of 1.35 as suggested by the data.

For the other states the curves shown are the predicted cross sections without a renormalization.

In conclusion, cross sections measured for inelastic pion scattering from ^{4}He show only small π^+/π^- asymmetries. The absolute differential cross sections are reproduced very well by predictions using the RCCSM wave functions. The RCCSM has been very successful in fitting a large body of data for the mass-4 system. The only data for which the RCCSM seems to fail are the absolute cross sections for $^4\mathrm{He}(\gamma,n)$ and thus the ratio R_γ below $E_x = 35$ MeV. Even without as thorough a theoretical treatment as the RCCSM provides, the pion scattering casts considerable doubt on the interpretation of the experimental value of R_γ in terms of isospin mixing due to a large CSB force. Our data show only a very small amount of isospin mixing between the excited states of ^{4}He.

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