Isospin Mixing of 4^- Particle-Hole States in ^{16}O

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Transitions to $(4^-, T=0)$ states in ^{16}O at 17.79 and 19.80 MeV are found to be strongly asymmetric in π^+ vs π^- inelastic scattering; in contrast, the π^+ and π^- cross sections for the $(4^-, T=1)$ state at 18.99 MeV are equal. Three-state isospin mixing is proposed as an explanation. Off-diagonal charge-dependent mixing matrix elements of -147 ± 25 and -99 ± 17 keV are obtained.

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We report the first observation of isospin mixing among three nuclear states which was detected by comparing π^+ and π^- inelastic scattering. This technique has been used to separate proton and neutron components of nuclear excitations at pion energies near the (3,3) resonance,[1] where the ratio of the cross sections for π^+ vs π^- scattering from protons (neutrons) is about 9:1 (1:9). Furthermore, a direct comparison of π^+ and π^- inelastic scattering at these energies from self-conjugate nuclei provides a method of detecting isospin impurities of the excited nuclear states.[2] In previous cases[3-7] of strong isospin mixing (^8Be, ^{12}C, and ^{16}O), only two states were believed to be involved.

Our study of π^+ and π^- inelastic scattering from ^{16}O at large momentum transfer was carried out on the Energetic Pion Channel and Spectrometer (EPICS) at the Clinton P. Anderson Meson Physics Facility, which has been described in detail elsewhere.[8] Ice targets of 160 and 320 mg/cm^2 thickness were used. The incident pion energy was 164 MeV, and the angular range was from 53° to 89° (laboratory). Typical energy resolution was 350 keV full width at half maximum (FWHM). The absolute cross sections were determined by scattering π^+ and π^- from the hydrogen in the ice targets and using the calculated π-p cross sections of Dodder.[9] The absolute normalization is believed to be accurate to approximately 10% whereas the relative π^+/π^- uncertainty is about 5%.

Spectra obtained from π^+ and π^- scattering at a laboratory angle of 77° are shown in Fig. 1. The $(4^-, T=0)$ states at 17.79 and 19.80 MeV show large π^+/π^- asymmetries, but the $(4^-, T=1)$ state at 18.98 MeV does not. Yields for these states were obtained by fitting the region between 16 and 23 MeV with a polynomial background and four peaks of fixed line shape, determined by the line shape of the elastic peak for each thickness of target. The relative energies of the three 4^- states were fixed at values obtained in previous studies,[10,11] while the state at ~20.5 MeV was fit when possible (its angular distribution appears to have a minimum near the 4^- maximum and

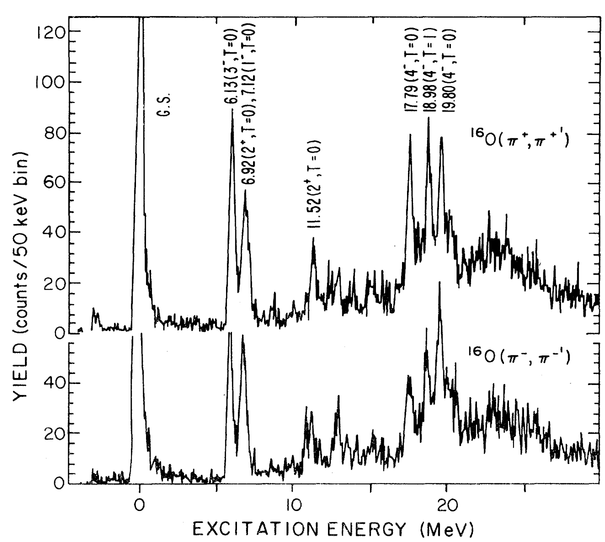

FIG. 1. Energy loss spectra for π^+ and π^- at an energy of 164 MeV and a laboratory angle of 77°.

may be a 3^- state). From the angular distributions shown in Fig. 2, one may obtain the following ratios of the summed yields for π^+ vs π^-: (1) 17.79 MeV ($4^-, T=0$), $R(\pi^+/\pi^-)=1.59\pm 0.12$; (2) 18.98 MeV ($4^-, T=1$), $R(\pi^+/\pi^-)=0.964\pm 0.080$; and (3) 19.80 MeV ($4^-, T=0$), $R(\pi^+/\pi^-)=0.605 \pm 0.049$. (Errors quoted are statistical.) From charge symmetry, these ratios are expected to be unity. For example, the low-lying ($3^-, T=0$) state at 6.13 MeV has a π^+/π^- cross section ratio of 0.98 ± 0.04 at 45°, which is near its maximum.

These states in ^{16}O, which have a $(d_{5/2}, p_{3/2}^{-1})$ configuration, have been seen in one-nucleon transfer reactions[10] and in inelastic proton scattering at medium energies.[11] The 18.98-MeV state ($4^-, T=1$) has also been observed in high-energy electron scattering.[12,13] The excitation energies of these states are well above particle threshold, and because medium-energy pions are strongly absorbed, one may expect π^+/π^- asymmetries to result from differences in proton and neutron single-particle wave functions. These continuum effects in the reaction channels have been investigated by Siciliano and Weiss[14] and cannot explain the asymmetries observed. The authors of Ref. 14 conclude that continuum effects would result in a systematic π^- bias in the cross sections for both $T=0$ and $T=1$ states, rather than a reversal of the π^+/π^- asymmetry as observed for the $T=0$ states. Our interpretation of the asymmetries for pion excitation of these states is that they are substantially mixed in isospin. In previous cases of two-state isospin mixing,[2-7] the $T_<$ state becomes mostly a proton state (π^+ enhanced) and the $T_>$ state is predominantly a neutron state (π^- enhanced). For ^{16}O, three 4^- states are known within 2 MeV so that three-state mixing has to be considered. The qualitative picture of the mixing in ^{16}O is that the two $T=0$ states mix through the $T=1$ state with nearly equal magnitudes. The lower state mixes with the middle state, resulting in the lower level becoming mostly a proton state and the middle level becoming mostly a neutron state. However, when the middle state mixes with the upper state, the energy denominator of the mixing changes sign, which results in the state above becoming primarily neutron in composition while the middle state gains in proton strength from this second mixing. Thus, the $T=1$ state retains nearly equal proton and neutron amplitudes, whereas the lower level becomes mostly a proton state and the upper level mostly a neutron state.

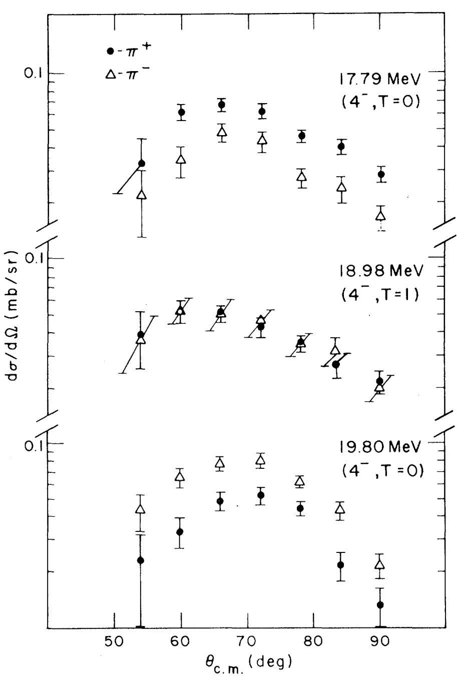

FIG. 2. Center-of-mass differential cross sections for $\pi^\pm$ scattering at 164 MeV.

If we assume that the charge-dependent part of the nuclear Hamiltonian, H_{cd}, may be treated as a small perturbation, we may write the physical states (labeled $|A'\rangle$, $|B'\rangle$, and $|C'\rangle$) as linear combinations of the unperturbed states of pure isospin (labeled $|A\rangle$, $|B\rangle$, and $|C\rangle$) as

$$\begin{aligned} |A'\rangle &= |A\rangle + \epsilon_1|B\rangle + \epsilon_3|C\rangle, \\ |B'\rangle &= -\epsilon_1|A\rangle + |B\rangle + \epsilon_2|C\rangle, \\ |C'\rangle &= -\epsilon_3|A\rangle - \epsilon_2|B\rangle + |C\rangle, \end{aligned} \tag{1}$$

where $\epsilon_1 = \langle A|H_{cd}|B\rangle/(E_A-E_B)$, $\epsilon_2=\langle B|H_{cd}|C\rangle/(E_B-E_C)$, and $\epsilon_3=\langle A|H_{cd}|C\rangle/(E_A-E_C)$. In these calculations we will ignore terms of order ϵ^2. The unperturbed 4^- states of ^{16}O must be configuration mixed as well because the single-particle, single-hole (1p-1h) configurations can result in only two states ($T=0,1$). Therefore, the unperturbed states are written as

$$\begin{aligned} |A\rangle &= \alpha|\,\text{1p-1h}, T=0\rangle + \textstyle\sum_i \alpha_i|\psi_i, T=0\rangle, \\ |B\rangle &= \beta|\,\text{1p-2h}, T=1\rangle + \textstyle\sum_i \beta_i|\psi_i, T=1\rangle, \\ |C\rangle &= \gamma|\,\text{1p-1h}, T=0\rangle + \textstyle\sum_i \gamma_i|\psi_i, T=0\rangle, \end{aligned} \tag{2}$$

where ψ_i labels possible multiparticle-multihole configurations.

At this point we make the assumption that the distorted-wave impulse approximation (DWIA) provides an adequate description of the pion-nucleus interaction.[15] This assumption treats the transition operator as a one-body operator on the nuclear space. We note that even from the complicated ground state of ^{16}O, which contains substantial 2p-2h admixtures,[16] the one-body density matrix elements for 2p-2h to 1p-1h transitions to the "stretched" 4^- states are identically zero, for 2p-2h configurations from the $p_{1/2}$ shell. Also, contributions of 2p-2h to 3p-3h transitions are dramatically reduced relative to the core to 1p-1h terms. Thus, within the model, only the 1p-1h amplitudes of Eq. (2) are reached.

If we further assume that the energy dependence of the π-nucleon interaction is dominated by the (3,3) channel, the DWIA π-nucleus amplitude for a 1p-1h, unnatural-parity transition from an even-even nucleus may be written as[14]

$$\Lambda_{\varphi_z}{}^T = F[(2+\varphi_z) + (-1)^T(2-\varphi_z)], \qquad (3)$$

where $\varphi_z = \pm 1$ ($\pi^\pm$) and T (=0, 1) is the nuclear isospin. The proton and neutron single-particle wave functions are assumed to be identical, and the differences between π^+ and π^- distorted waves are neglected. The factor F contains all of the details common to the $\pi^\pm$ excitation of the unperturbed states at the same incident pion energy and momentum transfer: distorted waves, radial integrals, angular-momentum recoupling coefficients, etc. Then, to order ϵ_i, the cross sections for $\pi^\pm$ scattering to the isospin mixed states may be written as

$$\begin{aligned}
\sigma_{\varphi_z}{}^{A'} &= |\hat{F}|^2 16\hat{\alpha}[\hat{\alpha} + 2\hat{\gamma}\epsilon_3 + \varphi_z\epsilon_1],\\
\sigma_{\varphi_z}{}^{B'} &= |\hat{F}|^2 4[1 + 4\varphi_z(\hat{\gamma}\epsilon_2 - \hat{\alpha}\epsilon_1)], \qquad (4)\\
\sigma_{\varphi_z}{}^{C'} &= |\hat{F}|^2 16\hat{\gamma}[\hat{\gamma} - 2\hat{\alpha}\epsilon_3 - \varphi_z\epsilon_2],
\end{aligned}$$

where $|\hat{F}|^2(\hat{\alpha},\hat{\gamma})$ is $|F|^2(\alpha,\gamma)$ multiplied (divided) by β^2 (β) because in the absence of a full DWIA calculation, the absolute magnitude of the 1p-1h strength cannot be determined.

The six summed cross sections for $\pi^\pm$ scattering to the three states were used with the above expressions to solve for the six quantities $\hat{\alpha}$, $\hat{\gamma}$, ϵ_1, ϵ_2, ϵ_3, and $|\hat{F}|^2$. The results of the calculation are shown in Table I. An identical analysis which kept all terms to order ϵ^2 yielded results unchanged from the present work.

The deduced 1p-1h amplitudes for these states are in qualitative agreement with the relative spectroscopic factors obtained by Mairle[9] in an ^{17}O$(d,t)^{16}$O experiment when the effects of isospin mixing are included, i.e., the 17.79-MeV state has less neutron p-h strength than the 19.80-MeV state, relative to the 18.98-MeV state. The fact that $\hat{\alpha}^2 + \hat{\gamma}^2 \leq 0.54$ indicates further fragmentation of the $T=0$ strength in the excitation spectrum. Because there is no experimental evidence for these other $T=0$ states, we assume that no more than the two observed (4^-, $T=0$) levels can mix significantly with the (4^-, $T=1$) state. If one assumes that β is unity, as is suggested by the studies of Mairle,[10] and neglects isospin mixing between the 1p-1h and 3p-3h configurations, the 1p-1h $\langle T=0|H_{cd}|T=1\rangle$ matrix element obtained is about -240 ± 40 keV. This value is somewhat uncertain, however, because small 3p-3h amplitudes in the $T=1$ state may significantly affect the exact value of the 1p-1h matrix element obtained, as well as the effects of isospin mixing between the 1p-1h and 3p-3h configurations. To determine 1p-1h or 3p-3h matrix elements accurately, it may be necessary to interpret our results within the

TABLE I. Values for the physical and unperturbed energies, configuration-mixing parameters, and the charge-dependent mixing matrix element are shown. Errors on $\hat{\alpha}$, $\hat{\gamma}$, $\langle A|H_{cd}|B\rangle$, $\langle B|H_{cd}|C\rangle$, $\langle A|H_{cd}|C\rangle$, and $|\hat{F}|^2$ are estimates based on the experimental errors. The DWIA parameter $|\hat{F}|^2 = 0.0625\pm 0.0034$ mb/sr. The values for the unperturbed energies do not include a diagonal charge-dependent energy shift.

Physical energy (MeV)	Unperturbed energy (MeV)	1p-1h amplitudes
17.79 ± 0.02	17.81 ± 0.02	$\hat{\alpha} = 0.510\pm 0.043$
18.98 ± 0.02	18.98 ± 0.02	
19.80 ± 0.02	19.78 ± 0.02	$\hat{\gamma} = 0.529\pm 0.046$
Charge-dependent mixing matrix elements		
$\langle A\|H_{cd}\|B\rangle = -147\pm 25$ keV		
$\langle B\|H_{cd}\|C\rangle = -99\pm 17$ keV		
$\langle A\|H_{cd}\|C\rangle = 17\pm 30$ keV		

framework of large-basis shell-model wave functions. Such an analysis is in progress.[17]

In conclusion, large asymmetries in π^+ vs π^- excitations of 4^- states in ^{16}O are interpreted as evidence of substantial isospin mixing among the states. Off-diagonal charge-dependent matrix elements of -147 ± 25 and -99 ± 17 keV are obtained when the data are analyzed with a simple model for three-state mixing. Before definite conclusions can be reached concerning the magnitude of charge-dependent forces in nuclei more experimental and theoretical study is needed; however, intermediate-energy pions will be a useful tool in the study of this aspect of nuclear structure.

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