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Identification of $\Delta S = 1$ Transitions in ^{13}C by Measurement of Pion Inelastic Excitation Functions

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Differential cross sections for $^{13}\mathrm{C}(\pi,\pi')$ were measured between 100 and 300 MeV for momentum transfers of $1.1\hbar$ fm^{-1} and $1.4\hbar$ fm^{-1}. In this energy range the different energy dependences of the spin-dependent and spin-independent parts of the pion-nucleon interaction provide a very sensitive method of discriminating between transitions that proceed with a spin transfer ($\Delta S = 1$) or without a spin transfer ($\Delta S = 0$). Five transitions in ^{13}C were found to be dominated by the $\Delta S = 1$ transition density amplitude.

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The work of Moore *et al.*[1] indicated that new information can be obtained from the measurement of inelastic pion excitation functions. In this Letter we report on the use of excitation functions of inelastic pion scattering to distinguish between $\Delta S = 0$ and $\Delta S = 1$ transitions, where ΔS is the spin transfer to the target nucleus. Differential cross sections for two transitions in ^{13}C, known to proceed predominantly by $\Delta S = 0$, were found to have energy dependences very different from that of a recently determined[2,3] pure $\Delta S = 1$, pure neutron particle-hole excitation of a stretched state. Four other transitions were found to be dominated by $\Delta S = 1$. Such an effect was also seen in the work of Cottingame *et al.*[4] in which natural and unnatural parity transitions in $^{12}\mathrm{C}(\pi,\pi')$ had dramatically different energy dependences. The explanation[5] of these different energy dependences is based on two facts. Firstly, at energies near the [3, 3] resonance the spin-dependent and spin-independent parts of the pion-nucleus scattering amplitude have quite different energy dependences for a given momentum transfer. Secondly, transitions that involve a spin transfer, $\Delta S = 1$, to the target can be caused only by the spin-dependent part of the force and transitions without a spin transfer, $\Delta S = 0$, are predominantly due to the spin-independent part of the force.

The pion-*nucleon* scattering amplitude can be written in the following form if the interaction is dominated by the [3, 3] resonance,[6]

$$f(k,k') = \alpha(k)(2\cos\theta + i\vec{\sigma}\cdot\hat{n}\sin\theta),$$

where k (k') is the pion momentum before (after) the collision, θ is the scattering angle in the pion-nucleon center-of-mass frame, $\vec{\sigma}$ is the spin operator for the nucleon, and $\hat{n}$ is the normal to the scattering plane. The coefficient $\alpha(k)$ is given in terms of the pion-nucleon phase shift δ by $\alpha(k) = k^{-1}\exp(i\delta)\sin\delta$. Only the operator $\vec{\sigma}\cdot\hat{n}$ can lead to a spin transfer ($\Delta S = 1$). Siciliano and Walker have shown that a similar expression holds for pion-*nucleus* scattering.[5] At a momentum transfer $q \simeq q_0$, i.e., near the maximum of the differential cross section $\sigma(\theta)$ for pion-nucleus scattering,

$$\sigma(\theta) = \Gamma(E)[4M^2(q_0)\cos^2(\theta) + S^2(q_0)\sin^2(\theta)],$$

if we assume dominance of the [3, 3] resonance, the validity of the fixed-scatterer impulse approximation and a one-step reaction mechanism. Here E is the pion energy and θ is the scattering angle in the pion-nucleus laboratory frame. Both the spin-independent form factor $M(q_0)$ and the spin-dependent form factor $S(q_0)$ contribute to natural parity transitions, but these transitions are usually dominated by $M(q_0)$. Only $S(q_0)$ can contribute to $\Delta S = 1$ transitions (if Fermi motion corrections are neglected). $\Gamma(E)$ contains the energy dependence of the pion-nucleon amplitudes, of the distortions, and the phase-space factors.[5]

At a constant momentum transfer q, the scattering angle θ is a simple function of the incident energy or wave number k, $\theta = 2\sin^{-1}(q/2k)$. For example, to keep the momentum transfer constant at a q value near the maximum in the angular distribution for a $\Delta L = 2$ transition in ^{13}C, the scattering angle must be decreased from about 72° at $T_\pi = 100$ MeV to about 32° at $T_\pi = 300$ MeV. (Because of its large width the [3, 3] resonance is dominant over this whole energy range.) Thus the energy dependence of $\sigma(\theta)$ for $\Delta S = 1$ transitions and $\Delta S = 0$ transitions measured at constant momentum transfer will be very different simply because of the difference between the $\sin^2\theta$ and $\cos^2\theta$ functions. The energy dependences of the $\sin^2\theta$ and $\cos^2\theta$ functions are expected to dominate the shapes of the excitation functions since $\Gamma(E)$ depends only relatively weakly on the energy for constant q. Consequently, the cross sections for $\Delta S = 1$ transitions should decrease with increasing energy since $\sin^2\theta$ decreases between 100 MeV ($\theta \simeq 72°$) and 300 MeV ($\theta \simeq 32°$). In contrast, the cross sections for $\Delta S = 0$ transitions should increase with increasing energy due to the associated $\cos^2\theta$ dependence.

We have measured excitation functions for inelastic scattering of pions from ^{13}C at incident energies between 100 and 300 MeV using the EPICS spectrometer at the Clinton P. Anderson Meson Physics Facility (LAMPF). The target was a 15 cm× 23 cm sheet of carbon, of areal density 210 mg/cm^2, enriched in ^{13}C to 99% and covered on both sides by thin ($\simeq 1$ mg/cm^2) Kapton foils. The energy resolution width was about 250 keV [full width at half maximum (FWHM)] (see Ref. 2 for typical pion spectra). At each energy the scattering angles were chosen to keep the momentum transfer fixed at either $1.1\hbar$ fm^{-1} or $1.4\hbar$ fm^{-1}. The former value is close to the first maximum in the angular distribution for a $\Delta L = 2$ transition and the latter is close to the maximum in the angular distribution for the strongly π^--enhanced transition to a state at 9.5 MeV.[2] At the smaller momentum transfer only π^+ data were taken; at the larger momentum transfer both π^+ and π^- data were taken and only the excitation function having the best statistics for each state (either π^+ or π^-) is presented here. To determine the overall normalization of the absolute cross sections, yields were measured for $\pi^\pm + p$ as a function of energy at $\theta_{lab} = 40°$ and compared with cross sections calculated with use of the pion-nucleon phase shifts of Rowe, Saloman, and Landau.[7] The error in the normalization is estimated as ± 10%.[8] This error is not included in the error bars of the figures which represent only the statistical and the fitting errors.

The $(\pi^+, \pi^{+\prime})$ cross sections for the transitions to the strongly excited $\frac{3}{2}^-$ state (3.68 MeV) and the unresolved $\frac{5}{2}^-$, $\frac{7}{2}^+$ doublet (7.5 MeV) were measured at $q = 1.1\hbar$ fm^{-1} and found to *increase* uniformly with energy (Fig. 1). The $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states are collectively enhanced and predicted to be dominated by the $\Delta L = 2$, $\Delta S = 0$ transition amplitude.[9] At $q = 1.1\hbar$ fm^{-1} the cross section measured for the doublet at 7.5 MeV is expected to be due mostly to the $\frac{5}{2}^-$ state and thus the excitation function for this group should show the features of a $\Delta S = 0$ transition, like the excitation function for the transition to the $\frac{3}{2}^-$ state. Indeed, for both states the simple $\cos^2\theta$ relation (Fig. 1, solid lines) predicts the trend of the data quite well. A distorted-wave impulse approximation (DWIA) calculation of the $\frac{3}{2}^-$ state with use of the code DWPI of Eisenstein and Miller[10] with an "energy-shifted" optical potential[11] and a simple collective form factor reproduces the shape of the excitation function in detail (Fig. 1, broken line). The relatively small differences between the $\cos^2\theta$ function and the DWIA result verify the claims made above regarding the weakness of the energy dependence of Γ.

The $(\pi^-, \pi^{-\prime})$ excitation function for the transition to the 9.5-MeV state was measured at $q = 1.4\hbar$ fm^{-1} and found to *decrease* uniformly with energy (Fig. 2), in sharp contrast to the data for

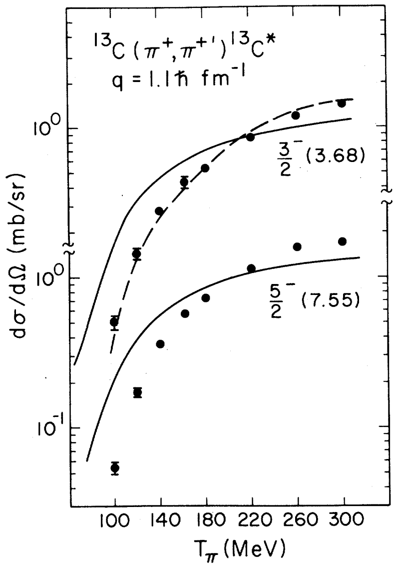

FIG. 1. Excitation functions for $^{13}C(\pi^+,\pi^{+\prime})$ to the $\frac{3}{2}^-$ (3.68 MeV) and $\frac{5}{2}^-$ (7.55 MeV) states measured at $q = 1.1\hbar$ fm^{-1}. The solid lines are the $\cos^2\theta$ dependences arbitrarily normalized to the data at 220 MeV. The dashed line is the result of a DWIA calculation for the $\frac{3}{2}^-$ state.

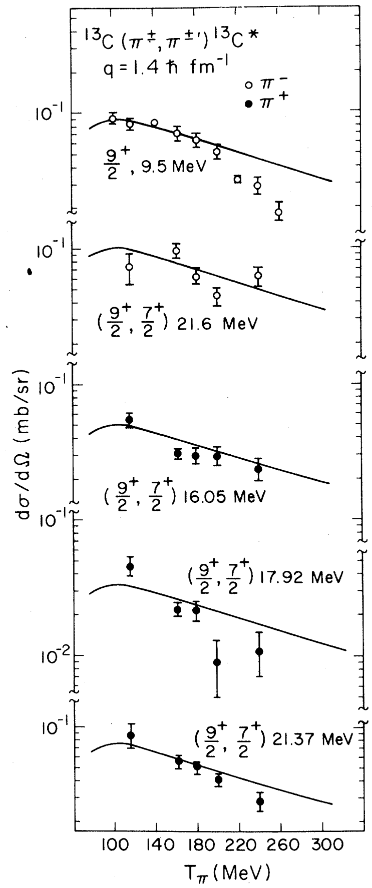

FIG. 2. Excitation functions for $^{13}C(\pi^\pm,\pi^{\pm\prime})$ to states at 9.5 and 21.60 MeV (with π^-), and at 16.05, 17.92, and 21.37 MeV (with π^+), measured at $q = 1.4\hbar$ fm^{-1}. The solid lines are simple $\sin^2\theta$ dependences.

the $\Delta S = 0$ transitions discussed above. The energy dependence is very well accounted for by $\sin^2\theta$ (solid line).

It has been proposed that this state is the $\frac{9}{2}^+$ member of a weak-coupling multiplet[12] based on a $1d_{5/2}$ neutron coupled to the first excited 2^+ state in ^{12}C. In this model the large π^- asymmetry, $A = [\sigma(\pi^-) - \sigma(\pi^+)]/[\sigma(\pi^-) + \sigma(\pi^+)] = 0.8 \pm 0.2$, can be explained as due to a pure neutron $1p_{3/2} \to 1d_{5/2}$ particle-hole excitation.[2] The shell-model calculations of Millener and Kurath[13] predict a $\frac{9}{2}^+$ state at 9.5 MeV which has a very large overlap with the weak-coupling state. The DWIA calculations of Lee and Kurath[3] with use of the Millener-Kurath wave functions reproduce not only the π^- enhancement very well but also the absolute cross sections[8] for exciting this state to within about 20%. According to this model, the $\frac{9}{2}^+$ state is reached solely by an unnatural parity transition with a total-angular-momentum transfer $\Delta J = 4$, an orbital-angular-momentum transfer $\Delta L = 3$, and a spin transfer $\Delta S = 1$. The experimental excitation function for this state from the present work is characteristic of a $\Delta S = 1$ transition, in excellent agreement with the shell-model calculation.[3,13]

We remark that the enhancement of $\Delta S = 1$ transitions relative to $\Delta S = 0$ transitions at low pion energies ($\simeq$ 100 MeV) is of considerable help in searches for weak unnatural parity transitions. At or above resonance (> 180 MeV) such transitions may be barely visible against a background of strong $\Delta S = 0$ transitions.

Four states, or groups of states, in the excitation energy region from 12 to 24 MeV were found to be strongly excited at large momentum transfer. Their angular distributions are fairly structureless and peak at large angles characteristic of a large angular-momentum transfer to high-spin states.[8] The centroids of these groups are at 16.05, 17.92, 21.37, and 21.60 MeV. Their excitation functions measured at $q = 1.4\hbar$ fm^{-1} are very similar to that of the $\frac{9}{2}^+$ state at 9.5 MeV and they are also very well described by $\sin^2\theta$ (Fig. 2). Thus the transitions to these states must be dominated by $\Delta S = 1$. The 16.05-MeV state is π^+ enhanced, $A = -0.6 \pm 0.2$ (Ref. 2), in agreement with the shell-model prediction[3,13] for a $\frac{9}{2}^+$ state close to 16 MeV. The complex close to 21.5-MeV peaks at 21.37 MeV in π^+ scattering and at 21.60 MeV in π^- scattering. The state or group of states at 17.92 MeV is excited about equally by both π^+ and π^-. An interpretation of these results in terms of shell-model predictions is difficult because of the large number of states involved. The 21.5-MeV complex probably contains several $\frac{7}{2}^+$ and $\frac{9}{2}^+$ states. Furthermore, the $T = \frac{1}{2}$ and $T = \frac{3}{2}$ states at these energies are most likely mixed in isospin. Isospin mixing was not included in Ref. 13 but its importance is suggested by the similarity of the pion spectra[2] close to 21.5 MeV in ^{13}C with those close to 19 MeV in ^{12}C (Ref. 14).

The 180° electron scattering data of Hicks *et al.*[15] and Dubach *et al.*[16] are in agreement with our $\Delta S = 1$ assignments for some of these transitions. They found $M4$ transitions to states at 9.49, 16.06, and 21.43 MeV but did not see any significant strength at $\simeq 17.9$ MeV. A comparison of the different excitation strengths from $(\pi^+, \pi^{+\prime})$, $(\pi^-, \pi^{-\prime})$, and (e, e') allows conclusions about the isospin transfer ΔT since the transverse (e, e') form factor is dominated by $\Delta T = 1$. The near equality of $\sigma(\pi^-)$ and $\sigma(\pi^+)$ for the group at 17.92 MeV suggests a pure isospin transfer of either $\Delta T = 0$ or $\Delta T = 1$, but the lack of any significant $M4$ strength from (e, e') strongly supports a pure $\Delta T = 0$ transition. The excitation energy of one of the strong $M4$ transitions from (e, e'), $E_x = 21.43 \pm 0.03$ MeV,[16] is close to the centroid of the peak seen in $(\pi^+, \pi^{+\prime})$. This suggests a concentration of the $\Delta T = 1$ strength in the lower-energy part of the 21.5-MeV complex.

In summary, these data have demonstrated the utility of measurements of excitation functions of inelastic pion scattering in the identification of $\Delta S = 1$ transitions. This technique has been used to confirm that the pure transition to the $\frac{9}{2}^+$ state at 9.5 MeV involves $\Delta S = 1$ and to identify four $\Delta S = 1$ transitions to states in the region from 12 to 24 MeV in ^{13}C. It is anticipated that this technique can be used to separate the $\Delta S = 0$ and $\Delta S = 1$ components of mixed transitions. This will allow stringent tests of shell-model predictions.

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