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TITLE SPIN EXCITATIONS IN PION INELASTIC SCATTERING

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Spin Excitations in Pion Inelastic Scattering

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INTRODUCTION

During the last few years a large amount of pion-nucleus (π-A) inelastic scattering data has been obtained with high-flux, high-resolution facilities such as the SUSI spectrometer at SIN and the EPICS spectrometer at LAMPF. The early studies for the most part concentrated on strong transitions to low-lying collective states. These studies have been reviewed in part in Ref. 1 . One unanticipated feature of π-A inelastic scattering that has become evident as the scope of studies has increased is the strong excitation of high-spin stretched states in light nuclei. By stretched states we mean those whose total angular momentum is the maximum achievable in a $1\hbar\omega$ particle-hole excitation. Transitions to stretched states have now been observed in almost all p-shell nuclei that have been studied, as well as in ^{28}Si.[2-8]

The strength of these transitions can be qualitatively understood by examining the pion-nucleon (π-N) interaction. Following Koltun[9], the π-N amplitude can be written as follows, if the interaction is dominated by the [3,3] resonance:

$$f(k,k') = \alpha(k)[2\cos(\theta) + i\,\vec{\sigma}\cdot\hat{n}\sin(\theta)] \tag{1}$$

where $\alpha(k)$ contains the energy dependence of the elementary π-N force, θ is the center-of-mass scattering angle, $\vec{\sigma}$ is the nucleon spin operator, and $\hat{n}$ is the normal to the scattering plane. Only the second term, which is proportional to the π-N spin-orbit operator, can induce a spin transfer. Petrovich and Love[10] have extracted the strength of the central and spin-orbit parts of the π-N interaction using the impulse approximation (IA) and the π-N phase shifts. Their results at 180 MeV, shown in Fig. 3 of Ref. 10, confirm the conclusions one would draw from the simple P_{33} result (eq. 1), namely that at small momentum transfers ($q < 1.2$ fm^{-1}) the central strength, t_c, is considerably larger than the spin-orbit strength, t_{LS}. At about $q = 1.4$ fm^{-1} ($\theta \approx 70^o$) the two strengths become comparable. The relative strengths of the central and spin-orbit interactions are the same for both isospin channels. The factor of two enhancement of the isoscalar over the isovector t-matrix that results from the isospin properties of the [3,3] resonance is also contained in the results of Petrovich and Love. It is this factor that gives pion inelastic scattering its unique sensitivity to the relative contributions of protons and neutrons to inelastic transitions.

EXCITATION FUNCTION MEASUREMENTS

$^{12}C(\pi,\pi')$

The strength with which stretched configurations are excited can be seen in Fig. 1 which shows a π^+, a π^-, and a difference ($\pi^- - \pi^+$) spectrum taken on ^{12}C at $T_\pi = 164$ MeV and $\theta_L = 70^o$. The very strong groups near 19 MeV have been identified as two 4^- states, one an essentially pure proton transition (19.25 MeV) and the other a pure neutron transition (19.65 MeV). The large π^-/π^+ asymmetry is understood[11] as due to nearly maximal isospin mixing between a T = 0 and a T = 1 4^- state. The shapes of the angular distributions for these transitions are well described using a transition density having a total angular momentum transfer $\Delta J = 4$, orbital angular momentum transfer $\Delta L = 3$, and spin transfer $\Delta S = 1$.[2]

It was observed by Moore, et al.[12] that excitation functions measured for these transitions were quite different from those measured for low-lying natural parity transitions. When excitation functions measured at constant momentum transfers[13] (near the maximum in $d\sigma/d\Omega(\theta)$) for the 4^- (19.25) and 2^- (18.36) states were compared with those for the 2^+ (4.44), 3^- (9.36) and 0^+ (7.65) states (Fig. 2) it was found that the cross sections for the unnatural-parity transitions decrease as the energy increases while the cross sections for the natural-parity transitions rise dramatically as the energy is raised.

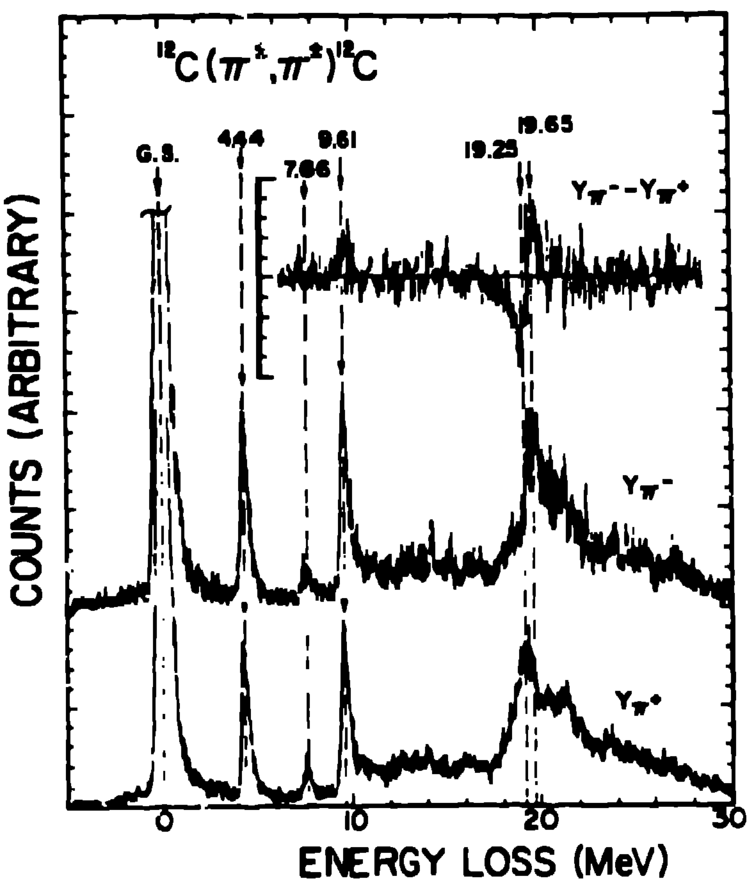

Fig. 1: π^+, π^-, and difference spectra for scattering fr .

Theoretical Interpretation of the Excitation Function Data

Siciliano and Walker[14] have provided a theoretical interpretation of the pion inelastic excitation-function data based on the assumptions of 1) the validity of the fixed-scatterer impulse approximation and 2) a one-step reaction mechanism. Their expression for the differential cross section for pion-nucleus inelastic scattering is:

$$\frac{d\sigma}{d\Omega} = \Gamma(E)[4M^2(q_0)\cos^2\theta + S^2(q_0)\sin^2\theta] \qquad (2)$$

where q_0 is a fixed momentum transfer near $d\sigma/d\Omega(q)_{max}$. In general only the S form factor can contribute to unnatural-parity transitions while both M and S can contribute to natural-parity transitions (although M usually dominates). The energy dependent factor $\Gamma(E)$ is a product of the distortion of the pion waves and

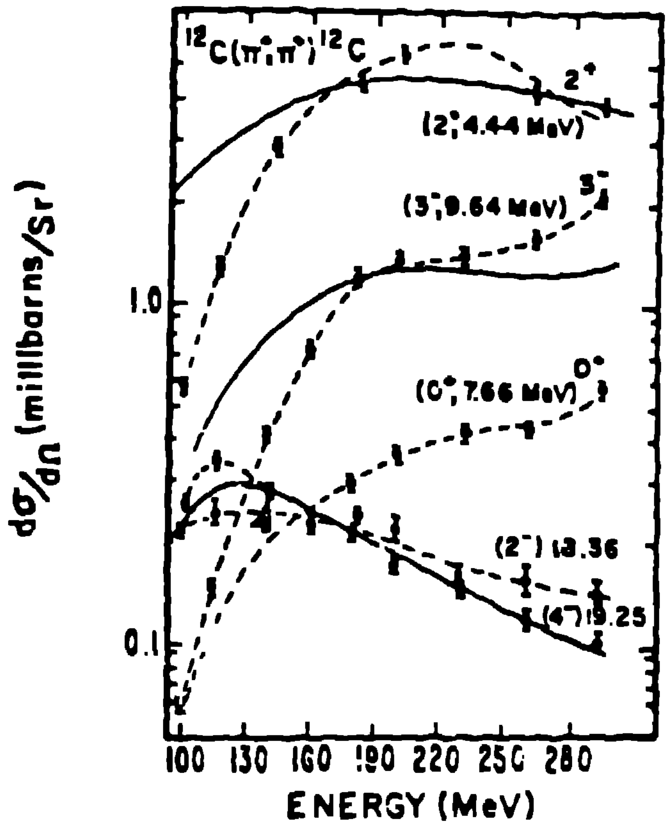

Fig. 2: Constant q excitation functions for (π,π') to states in ^{12}C.

the energy dependence of the elementary π-N force. Since the effect of attenuating the pion waves varies approximately as the inverse of the strength of the force, $\Gamma(E)$ is roughly constant in the vicinity of the [3,3] resonance. The energy dependence of pion-nucleus scattering is given by the $\cos^2\theta$ and $\sin^2\theta$ dependences of the pion-nucleon scattering amplitude. These angular dependences result in an energy dependence for constant q because the scattering angle must be adjusted as a function of energy to keep the momentum transfer constant. This results in $\Delta S = 1$ transitions decreasing with increasing energy since only the S form factor with its accompanying $\sin^2\theta$ dependence can contribute to unnatural-parity excitations. It should be noted that while in general Fermi motion corrections can allow the central part of the pion-nucleon interaction to contribute to unnatural-parity transitions they cannot contribute to the excitation of stretched configurations.

The solid lines in Fig. 2 are the simple $\cos^2\theta$ and $\sin^2\theta$ predictions of Siciliano and Walker. The 4^- and 2^- data are well represented by the $\sin^2\theta$ energy dependence. The $\cos^2\theta$ curves reproduce qualitatively the energy dependence of the natural-parity transitions. The discrepancies are due to the non-constant nature of $\Gamma(E)$ which will be discussed in more detail in the next section.

Application to Transitions in ^{13}C

In an odd mass nucleus more than one total angular momentum transfer is generally allowed and hence there are few pure unnatural-parity transitions. The main exceptions are transitions to stretched states where a spin transfer is required to reach the total angular momentum transfer necessary. One such state is the 9.5 MeV $9/2^+$ state in ^{13}C. The shapes of the (π,π') angular distributions for this state are characteristic of the $\Delta J = 4$, $\Delta L = 3$, $\Delta S = 1$ transition density amplitude.[3] The ratio of $\sigma(\pi^-)/\sigma(\pi^+) = 10\pm2$ has indicated that this state is reached by a pure neutron particle-hole excitation[15]. The pure neutron nature of the transition has been explained in a simple weak-coupling model as well as in a DWIA calculation using Millener-Kurath wave functions for their first predicted $9/2^+$ state.[3](see Sec. III) The shell-model wave functions predict a transition density that is pure $\Delta S = 1$.

The constant-q excitation function for π^- scattering to this state is shown in the lower part of Fig. 3 (diamonds). The energy dependence is similar to that of the unnatural-parity transitions in ^{12}C and is reproduced very well by the simple $\sin^2\theta$ dependence. The upper data in Fig. 3 (solid circles) is for the collectively-enhanced transition to the $3/2^-$ state (3.68 MeV) which is understood to be predominantly $\Delta S = 0$. The solid curve is the $\cos^2\theta$ prediction and the dashed curve is the result of a DWIA calculation[16] using a collective form factor and normalized to the data at 162 MeV. The energy dependence predicted by the DWIA is in very good agreement with the data.

The excitation function for the $9/2^+$ state provides striking confirmation of the $\Delta S = 1$ nature of the transition as deduced from the angular distributions. The knowledge of the spin transfer in a transition is very useful for testing wave functions as well as for determining the spin and parity of states in nuclei with spin-zero ground states. This method has been used to identify four other M4 transitions in ^{13}C.[17]

This technique has proven very complementary to the measurement of 180° electron scattering, for two reasons. The first is that 180° (e,e') is sensitive essentially only to $\Delta T = 1$ transitions whereas pion scattering excites $\Delta T = 0$ and $\Delta T = 1$

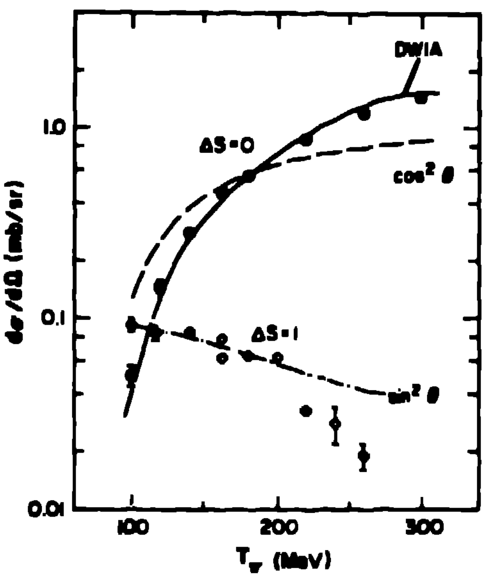

Fig. 3: Constant q excitation function for the $3/2^-$ (circles) and $9/2^+$ (diamonds) states in ^{13}C.

transitions in the ratio of 4/1. The second reason is the sensitivity of π^+ and π^- comparisons to the relative contributions of neutrons and protons. ^{13}C gives a good example of the ultility of these comparisons. The first $9/2^+$ state (9.5 MeV) is reached by a pure neutron excitation while the second (16.1 MeV) is reached by a transition that involves mostly protons. Both of these transitions have been observed in 180^0 (e,e')[16]. The third M4 transition is excited about equally by π^+ and π^-, indicating a pure isospin transfer. This state is not seen in (e,e') indicating that the transition is probably pure $\Delta T = 0$.

EXCITATION OF STRETCHED STATES

P-Shell Nuclei

Stretched one-particle one-hole states are those states having the maximum total angular momentum allowed in a single particle-hole excitation; i.e. $\Delta J = \ell_p + \ell_h + 1$, where ℓ_p (ℓ_h) is the particle (hole) orbital angular momentum and the orbital angular momentum transfer is $\Delta L = \ell_p + \ell_h$. Whenever ΔJ equals $\Delta L + 1$, states are reached by unnatural-parity transitions. In the p-shell, stretched states are made from $p_{3/2}{\cdot}d_{5/2}$ particle-hole excitations and are thus reached by M4 transitions ($\Delta J = 4$, $\Delta L = 3$, $\Delta S = 1$). Measurements of angular distributions are sensitive to the transferred J, L, and S, whereas excitation functions are sensitive to the spin transfer. These two together are very useful for locating stretched states. Because of the limited configurations that can make up stretched states they are ideal tests for the shell model. Fig. 4 shows the distribution of M4 transitions that have been measured in p-shell nuclei using π^+ and π^- inelastic scattering. M4 transitions in ^{11}B, ^{14}N, ^{14}C, and ^{16}O are shown along with those in ^{12}C and ^{13}C that have been previously discussed. Preliminary results for ^{15}N not contained in Fig. 4 will also be presented in this section.

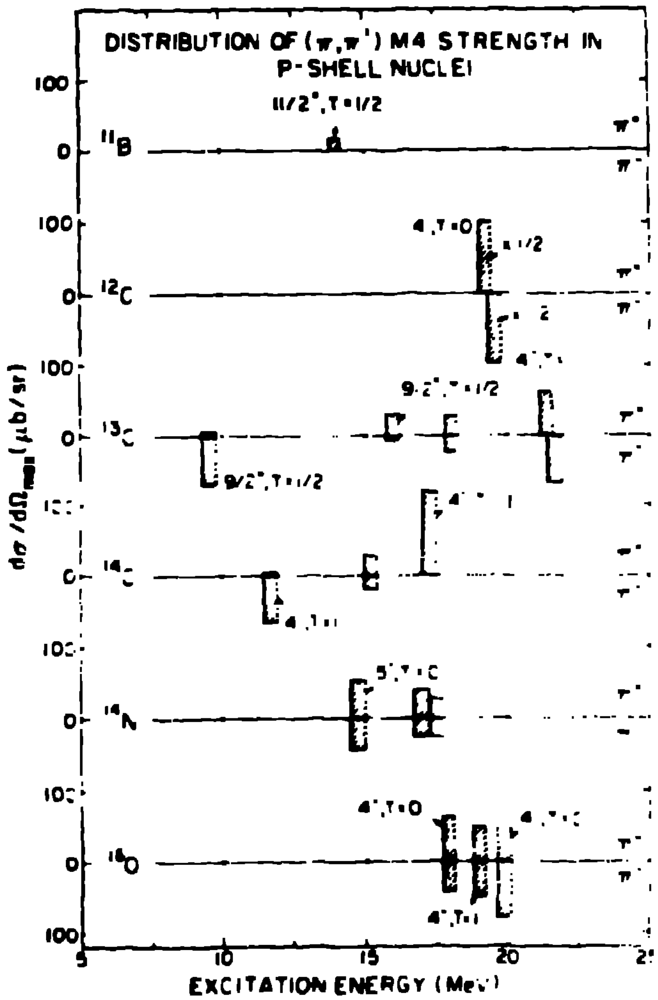

Fig. 4: Plot of (π,π') cross sections for M4 transitions in the p-shell.

The lightest nucleus in which an M4 transition has been observed is ^{11}B. The data of Zupransky, et al.[19] in Fig. 5 shows spectra for π^+ and π^- scattering from ^{11}B at T_π = 162 MeV and Θ_{lab} = 70°. The 11/2$^+$ state at 14.04 MeV can be seen to be excited much more strongly by π^- than by π^+, with a lower limit[19] of $R(=\sigma(\pi^-)/\sigma(\pi^+)) > 5$. An angular distribution and excitation function measured for π^- scattering indicate that this state is reached by an M4 transition. The large π^- enhancement is easily understood because the proton $d_{5/2}p_{3/2}^{-1}$ particle-hole excitations that can form 11/2$^+$ states in ^{11}B require a recoupling of the remaining $p_{3/2}$-shell protons. Such configurations cannot be reached in a single-step from the ground state. Microscopic DWIA calculations using the wave function of D. Kurath for the first 11/2$^+$ state in ^{11}B predict a large ratio $\sigma(\pi^-)/\sigma(\pi^+)$ and require an overall renormalization[8] factor of .22 is to fit the absolute magnitude of the data. This renormalization factor is smaller than that required with Millener-Kurath wave functions to fit the data for the ^{13}C 9/2$^+$ state.

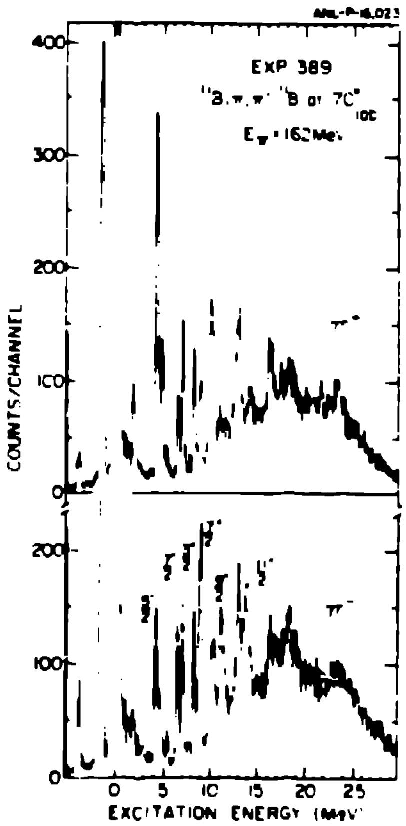

Fig. 5: Spectra for π^+ and π^- scattering from ^{11}B at T_π = 162 MeV.

As mentioned already, the M4 strength in ^{12}C is concentrated in two 4^- states, which are strongly isospin mixed. In ^{13}C there is a group at slightly higher excitation energy which shows a similar π^-/π^+ asymmetry indicating that these states in ^{13}C (which are reached by M4 transitions) have a large parentage in $^{12}C(4^-) \otimes \nu(p_{1/2})$.

The π^+ and π^- angular distributions for the 9.5-MeV $9/2^+$ state in ^{13}C are shown in Fig. 6. The solid curves are microscopic DWIA[20] calculations using the code ALLWRLD[21] to generate transition densities from the particle-hole amplitudes of Lee and Kurath with a harmonic oscillator parameter α = .632 fm^{-1}. The value of α required to reproduce the shape of the data is considerably smaller than that needed to fit[22] the transverse form factor measured in (e,e′), although it is nearly the same as the

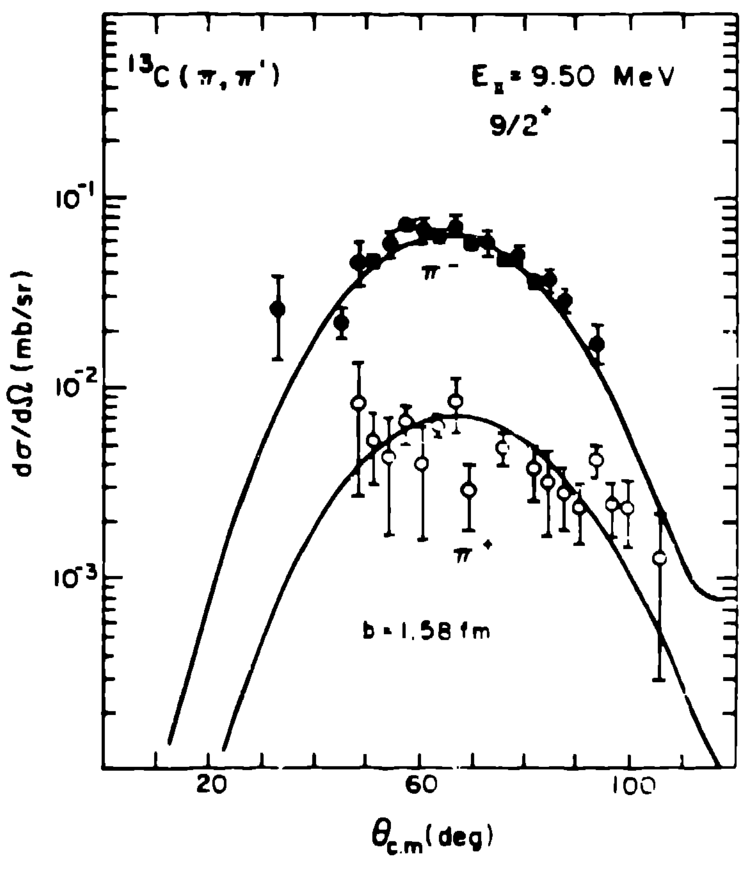

Fig. 6: Angular distributions for π^+ and π^- scattering to 9.5-MeV $9/2^+$ state in ^{13}C.

value required to fit the 547 MeV (p,p′) data for this transition[23]. The overall renormalization required is .4, considerably smaller than that required to fit the transverse form factor from (e,e′) (.7).

Spectra for π^+ and π^- scattering[6] from ^{14}C, in which two 4^-, T = 1 states can be seen, are presented in Fig. 7 . The lower energy state (11.67 MeV) is π^- enhanced while the upper (17.26 MeV) is π^+ enhanced. Both ratios $\sigma(\pi^-)/\sigma(\pi^+)$ are larger than the free $\pi + n$ ($\pi + p$) values of 9 (1/9). These data have been compared with DWIA calculations[24] for $d_{5/2}p_{3/2}^{-1}$ particle-hole excitations to derive isoscalar and isovector spectroscopic amplitudes. The equation that must be solved to extract the relative isoscalar and isovector components from the measured ratio $\sigma(\pi^+)/\sigma(\pi^-)$,

$$R = \frac{\sigma(\pi^+)}{\sigma(\pi^-)} = \frac{(2S_0 - S_1)^2}{(2S_0 + S_1)^2} \qquad (3)$$

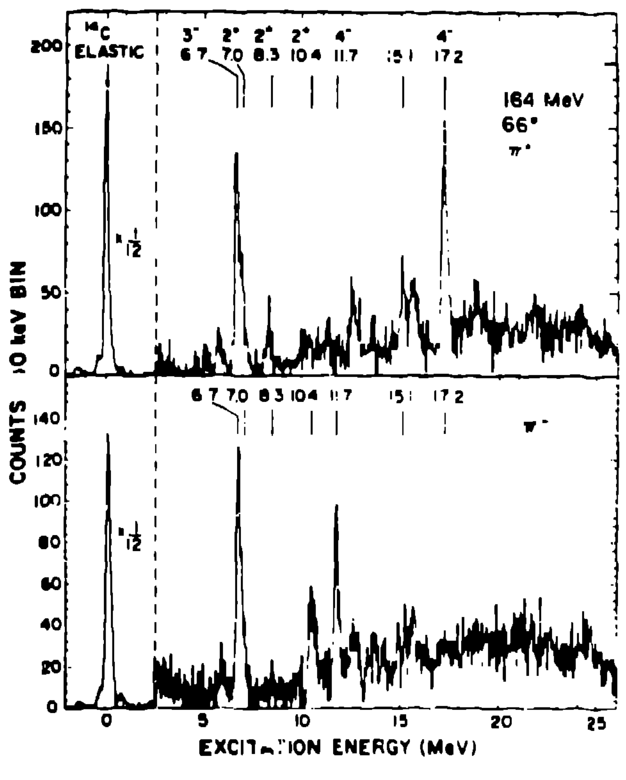

Fig. 7: Spectra for π^+ and π^- scattering from ^{14}C at T_π = 164 MeV.

has two solutions. This results in an ambiguity in the final result for S_1 and S_0. This must be eliminated through a comparison with electron and/or proton scattering data.

The strongest M4 transition observed in ^{14}N is to a 5^- state at 14.7 MeV (Fig. 8, Geesaman[7] *et al.*). The π^+ and π^- cross sections for this transition are approximately equal, indicating that there is no significant isospin mixing. A quenching factor of .70 is needed to obtain agreement between the magnitude of the data and DWIA calculations for the lowest 5^- state predicted by D. Kurath[7]. These wave functions predict 51% of the 5^- strength to be in the lowest 5^- with the remainder split between states at 17.3 and 18.0 MeV. These model states have been tentatively identified with groups seen at 16.86 and 17.46 MeV. The angular distributions and total strengths of these groups indicate that they contain additional unresolved states of other multipolarities.

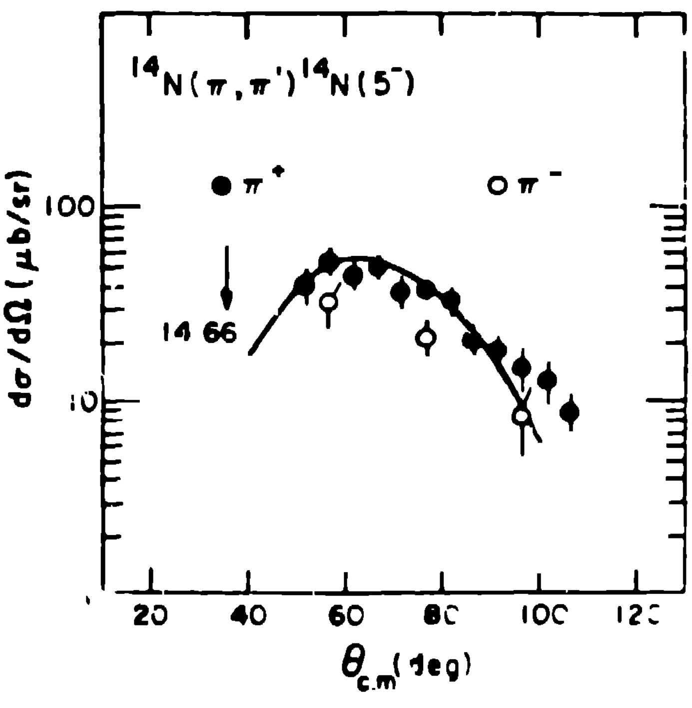

Fig. 8: Angular distributions for π^+ and π^- scattering to 14.7-MeV 5^- state in ^{14}N.

Very recently π^+ and π^- spectra for scattering from ^{15}N have been measured. Fig. 9 shows a π^+ and a π^- spectrum taken at $\theta_{lab} = 65^o$ and $T_\pi = 164$ MeV. Previously identified $9/2^+$ states at 10.7 and 12.6 MeV are labeled as well as a very strong state at 17.2 MeV which is possibly reached by an M4 transition. The two lowest $9/2^+$ states are very strongly π^+ enhanced, while the state at 17.2 MeV is slightly π^- enhanced. Shell model calculations of D. J. Millener[25] using a $1\hbar\omega$ basis predict a very large π^+/π^- ratio for the first $9/2^+$ state in ^{15}N. When 3p-4h terms are included in the calculation, this state is split into two states, which can be identified with the 10.7 and 12.6 MeV states.

The last p-shell nucleus for which we present data on the excitation of stretched configurations is ^{16}O. Fig. 10 shows angular distributions for three 4^- states excited in (π,π') on ^{16}O

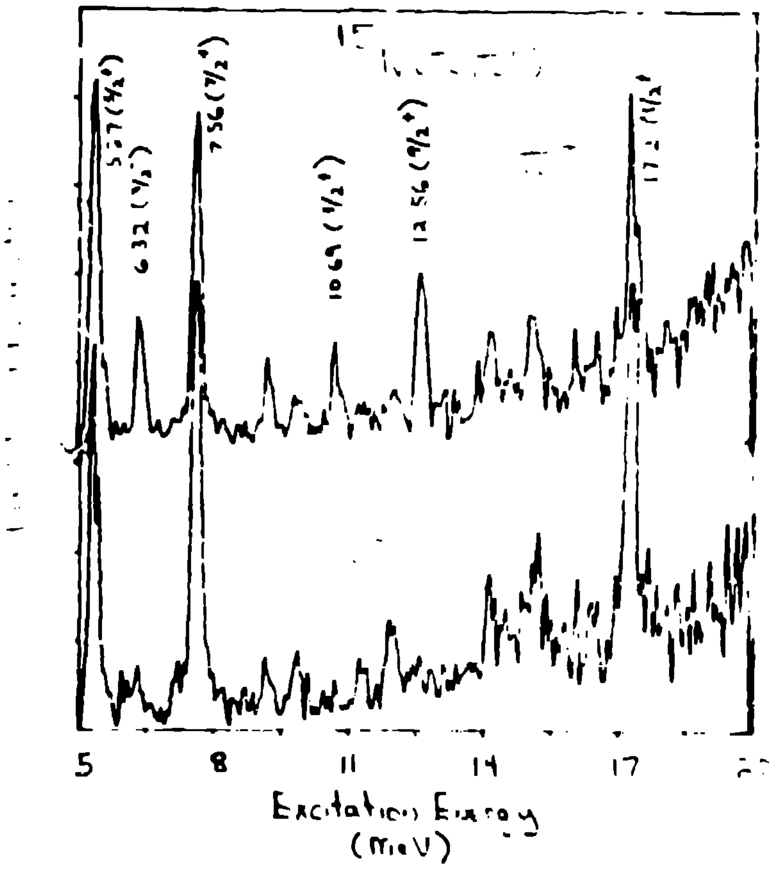

Fig. 9: Spectra for π^+ and π^- scattering from ^{15}N at T_π = 164 MeV.

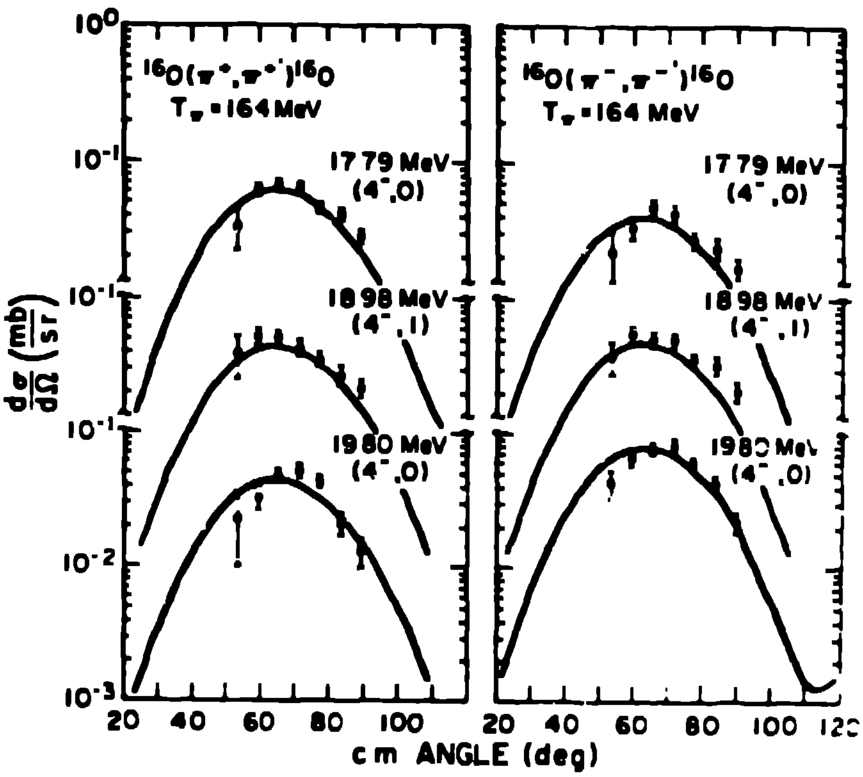

Fig. 10: Angular distributions for π^+ and π^- scattering to isospin-mixed 4^- states in ^{16}O.

(T = 0 17.79 and 19.80 MeV, T = 1 18.98 MeV). The observed ratios $\sigma(\pi^+)/\sigma(\pi^-)$ indicate that these states are weakly isospin mixed. The solid curves are calculations using a $d_{5/2}p_{3/2}^{-1}$ transition density and a spectroscopic factor for the T = 1 state determined from electron scattering. The isospin mixing matrix elements derived from the pion scattering greatly improve the agreement of calculations with the electron scattering data to the lower T = 0 state.

Stretched States in Heavier Nuclei

^{28}Si is the only nucleus outside the p-shell for which excitations of stretched states have been measured with pion inelastic scattering. Fig. 11 shows angular distributions measured[4] for 6^- T = 0,1 and 5^-, T = 0 states. The solid curves for the 6^- states are calculated using a $f_{7/2}d_{5/2}^{-1}$ transition density and squared spectroscopic factors of .13 for the T = 0 state and .34 for the T = 1 state. The spectroscopic factor for

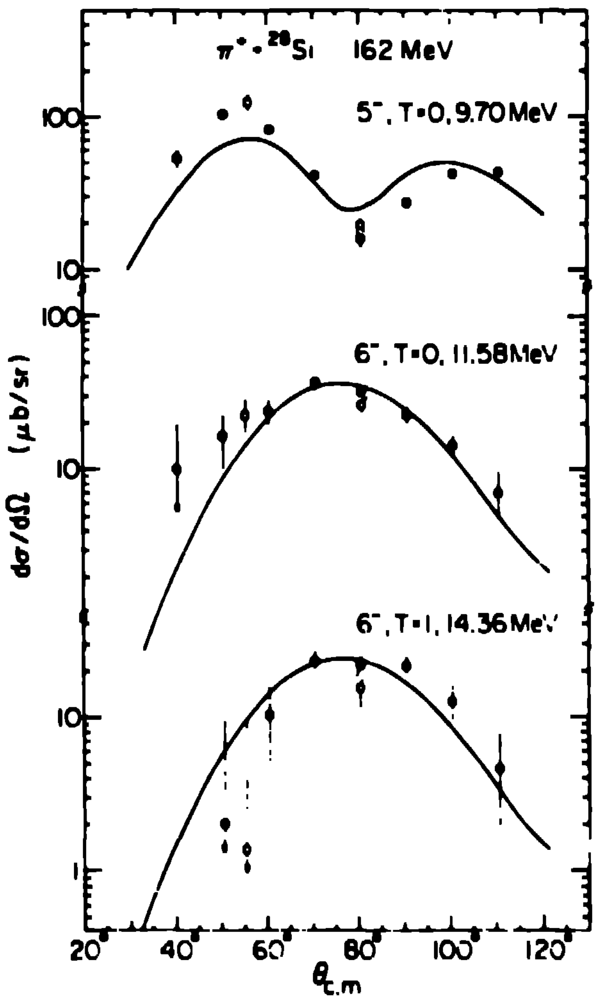

Fig. 11: Angular distributions for π^+ and π^- scattering to 5^- and 6^- states in ^{28}Si.

the T = 1 state is consistent with that necessary to reproduce proton and electron scattering data for this transition. Recent (p,p') measurements[26] have indicated different structure for the T = 0 and T = 1 6^- states in ^{28}Si that is consistent with the isoscalar and isovector spectroscopic factors determined in the pion scattering measurements.

SPIN EXCITATIONS OF NON-STRETCHED CONFIGURATIONS

Although the majority of spin excitations that have been observed in pion inelastic scattering are transitions to stretched states, there are a few examples of $\Delta S = 1$ excitation of non-stretched states. The best studied of these have been the 1^+ $T = 0$ (12.71 MeV) and $T = 1$ (15.11 MeV) states in ^{12}C. Comparisons of π^+ and π^- cross sections for these states have indicated the presence of isospin mixing.[27] A constant-q excitation function measured for the $T = 0$ state shows the energy dependence expected for a pure $\Delta S = 1$ transition. The $T = 1$ state excitation function shows an unexpected bump near at 180 MeV. The interpretation of this anomolous excitation function as due to admixtures of ΔN^{-1} admixtures in the 15.11-MeV state wave function[28] will be discussed in another presentation.[29]

Most of the spin excitations seen in (π,π') have been transitions which are required by parity or angular momentum conservation to have a non-zero spin transfer. A natural-parity transition to a 1^- state (4.45 MeV) in ^{18}O recently observed[30] in (π,π') seems to be dominated by $\Delta S = 1$. The $\Delta S = 1$ assignment is based on the angular distribution, shown in Fig. 12. A number of

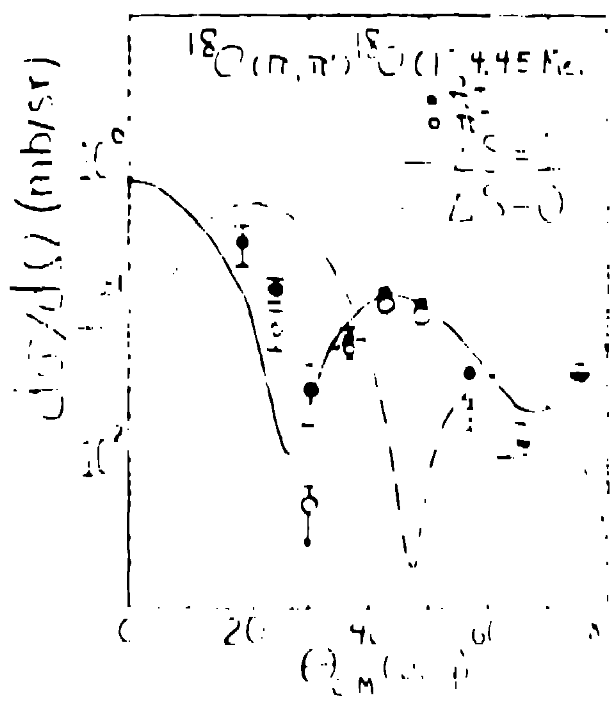

Fig. 12: Angular distributions for π^+ and π^- scattering to 4.45-MeV 1^- state in ^{18}O.

DWIA and eikonal model calculations have predicted dramatically different angular distributions for transitions to 1^-, $\Delta S = 0$ and 1^-, $\Delta S = 1$ states. The solid curve in Fig. 12, generated using the DWIA code ARPIN[30], is for a pure $\Delta L = 1$, $\Delta S = 1$ transition and the dashed curve is for pure $\Delta L = 1$, $\Delta S = 0$. The two calculations are completely out of phase and only the $\Delta S = 1$ calculation reproduces the data. This data represents the first experimental confirmation of the different angular distributions predicted for $\Delta S = 0$ and $\Delta S = 1$ transitions.

A similar effect has been seen[32] in ^{12}C for the excitation of states near 25 MeV. Spectra taken at $T_\pi = 180$ MeV and $\theta_{lab} = 25^\circ$ for π^+, π^-, and the difference between them are shown in Fig. 13, along with a fit to the data. The large peak at 22.1 MeV is probably the well-known isovector giant dipole resonance and peaks at 18.3 and 19.3 MeV are an isospin-mixed doublet of 2^- states. The angular distributions for the 23.7 and 25.6 MeV groups are much less forward peaked than that of the 22.1-MeV state. In addition, these angular distributions resemble neither the

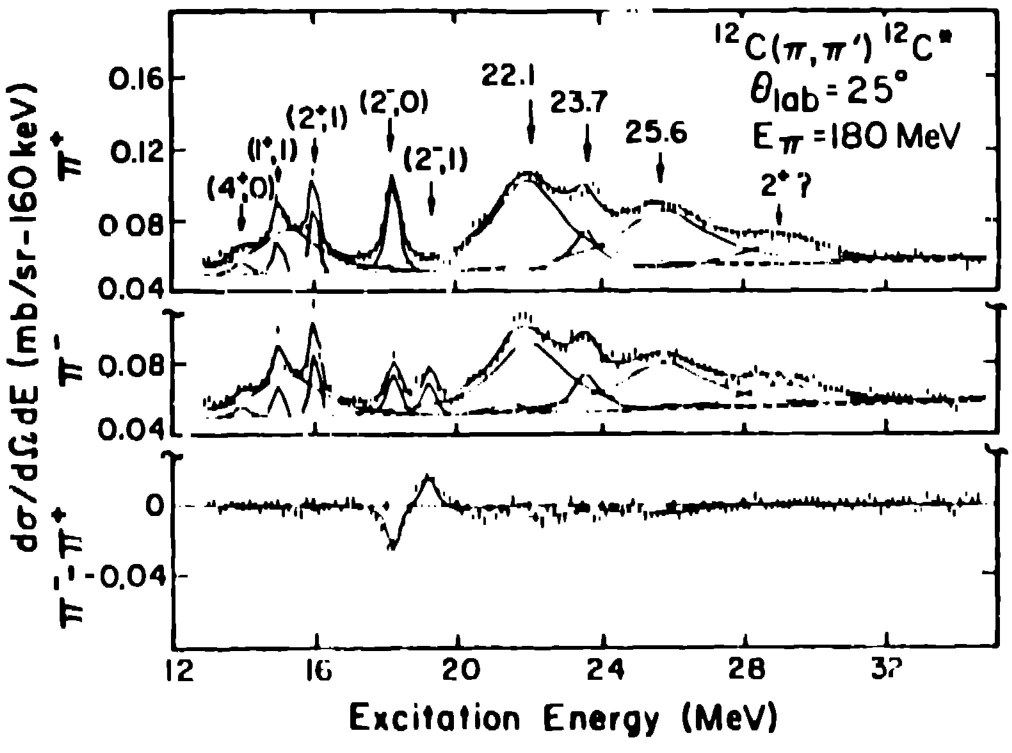

Fig. 13: π^+, π^-, and difference spectra for scattering to the giant dipole region of ^{12}C.

predicted shapes for 1^-, T = 1 or 2^- states. (The 18 and 19 MeV 2^- data are well described by the 2^- shapes.) The experimental angular distributions can be fitted with a combination of 1^- and 2^- calculations, but this requires a total 2^- strength exceeding the sum rule limit[31]. This sugggests the presence of some 1^-, $\Delta S = 1$ strength in this region. The summed cross sections for the 22.1, 23.7, and 25.6 MeV levels as well as the 18.3 and 19.3 MeV 2^- states can be fitted with a combination of 1^- T = 1 $\Delta S = 0$, 1^- T = 0,1 $\Delta S = 1$, and 2^- T = 0,1 for all allowed p to d excitations.

CONCLUSION

This paper has reviewed the data on spin excitations observed in pion inelastic scattering. A predominant feature of this process is the selectivity with which high-spin unnatural-parity states are excited. Constant-q excitation functions have proven valuable in identifying unnatural-parity states because of the unique signature of $\Delta S = 1$ transitions. It has recently been shown that angular distributions measured for transitions to natural-parity states are quite different for $\Delta S = 0$ and $\Delta S = 1$ transitions. Pion scattering should continue to prove useful in studying the spin structure of nuclear transitions because of the sensitivity of both excitation functions and angular distributions to the spin transferred to the nucleus. In particular, pion scattering measurements may be helpful in searches for spin-mode giant resonances.

In addition to the ability to distinguish transitions dominated by $\Delta S = 1$, comparisons of π^+ and π^- scattering can be used to determine the relative contributions of neutrons and protons to inelastic transitions. In each $N \neq Z$ nucleus studied there have been large π^+/π^- asymmetries observed for some transitions to stretched states. This results in information that is not obtainable from 180° electron scattering.

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