# Excitation of the $1^+$ state in $^{48}$Ca(10.2 MeV) by inelastic scattering of $\pi^-$ and $\pi^+$

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(Received 27 February 1984)

Excitation functions for inelastic scattering of $\pi^-$ from $^{48}$Ca to the $1^+$ state at 10.2 MeV have been measured at constant momentum transfer $q=73$ MeV/$c$. The incident energy was varied between 116 and 180 MeV. An upper limit was measured for the $\pi^+$ cross section at 116 MeV. The data are not fitted by distorted-wave impulse approximation calculations at this $q$ where the differential cross section is predicted to have its maximum. The discrepancy between theory and experiment is similar to the disagreement observed for $^{12}$C$(\pi,\pi')^{12}$C$(1^+$,15.1 MeV).

## I. INTRODUCTION

At present there is considerable interest in the quenching of magnetic transitions and its possible relationship to $\Delta_{3/2,3/2}$ (1232 MeV) degrees of freedom in nuclei.[1–9] Several comprehensive studies[1] of this problem have recently been presented. The transition to the $1^+$ state in $^{48}$Ca(10.2 MeV) is especially suited for such studies because of its expected simple structure. This state was first observed in inelastic electron scattering[10,11] and its analog state was observed in $^{48}$Ca(p,n)$^{48}$Sc.[12] The transition to this state has also been investigated by inelastic proton scattering.[13–17] One common feature of all these studies is the observation of a quenching of the $M1$ strength [expected in the extreme $(f_{7/2})^{8n}$ shell model] by a factor of about 0.3. The most recent value for the $B(M1)$ extracted from electron scattering[10] is $3.8\pm0.3\ \mu_N^2$, in contrast to $12\ \mu_N^2$ predicted by the extreme shell model. A total of 18 very weakly-excited $1^+$ states were also detected in (e,e′), but the summed $M1$ strength for these states is only about $1.5\ \mu_N^2$. This brings the total $B(M1)$ for all identified $M1$ transitions[10] to $5.3\pm0.6\ \mu_N^2$.

A shell-model calculation in the complete $(1f2p)^{8n}$ model space[18] accounts for part of the quenching by configuration mixing which reduces the single particle limit of $12\ \mu_N^2$ to $8.96\ \mu_N^2$ for the summed strength for all theoretical states. Most ($7.35\ \mu_N^2$) of the theoretical strength is contained in the transition to one state so that the ratio of the strongest experimental over the strongest theoretical $B(M1)$ value is $B_{\text{exp}}(M1)/B_{\text{th}}(M1)=0.52$. It seems unlikely that a further expansion of the shell-model space will explain the still missing strength by configuration mixing alone.

Meson exchange current (MEC) effects and effects due to $\Delta$-particle—nucleon-hole ($\Delta N^{-1}$) admixtures in the $1^+$-state wave function have recently been calculated.[9] Each of these reduces the transition amplitude: MEC by 7% and $\Delta N^{-1}$ admixtures by 11%, so that the total theoretical $M1$ strength is $5.6\ \mu_N^2$, which is consistent with experiment.

All of the analyses of the (e,e′), (p,p′), and (p,n) data known to us assume a closed $2s\,1d$ shell for both protons and neutrons in the ground state and the $1^+$ state in $^{48}$Ca. In this case, the $0^+\to1^+$ transition is a pure neutron transition. The magnitude of proton admixtures in this transition has been estimated theoretically.[19] In that work the proton part of the $M1$ transition was calculated to be negligibly small when a ground state proton occupation number determined from a $^{48}$Ca(d,$^3$He) experiment[20] was used.

One way to test experimentally the validity of the assumption of a pure neutron transition is by measurement of $\pi^-$ vs $\pi^+$ inelastic scattering. Near the $\Delta_{3/2,3/2}$ (1232) pion-nucleon resonance the $\pi^-$-neutron interaction is approximately three times as strong as the $\pi^+$-neutron interaction. Thus, the cross section ratio $\sigma(\pi^-)/\sigma(\pi^+)$ measured at pion energies near 180 MeV should be close to 9 if the reaction proceeds by a simple neutron one-particle—one-hole (1p-1h) excitation with respect to the target ground state. Nearly pure 1p-1h excitations have been observed in pion scattering to high-spin stretched states in the $1p$ shell,[21–23] and DWIA analyses[22,24,25] of these data using shell model transition densities have been successful.

However, $(\pi,\pi')$ data[26] for the transition to the $1^+,T=1$ state in $^{12}$C(15.1 MeV) could not be fitted by DWIA calculations. Contributions from a direct excitation of $\Delta N^{-1}$ components in the $1^+,T=1$ state have been suggested[26] as a possible explanation for these data, but no satisfactory theoretical reaction calculation has been presented so far. Of course, if $(\pi,\pi')$ reactions are to be used to extract nuclear structure information, the reaction mechanism needs to be understood. This is not the case yet for the transition to the $1^+,T=1$ state in $^{12}$C. In this work we find that a similar problem exists for the transition to the $1^+$ state in $^{48}$Ca. The differential cross sections measured at constant momentum transfer increase with increasing energy, in contrast to DWIA calculations, which predict a decrease. No information on proton admixtures in the transition density could be obtained due to difficulties in extracting the very small $(\pi^+,\pi^{+\prime})$ cross sections from the spectra because of an unexpectedly large oxygen content in the $^{48}$Ca target. We intend to continue this experiment if the (very expensive) rehabilitation of the target can be completed.

## II. EXPERIMENT

The energetic pion channel and spectrometer (EPICS) system[27,28] at the Clinton P. Anderson Meson Physics Facility (LAMPF) was used to take excitation energy spectra for inelastic scattering of $\pi^+$ and $\pi^-$ from $^{48}$Ca. The target consisted of four foils, each of dimension 5.0 cm$\times$3.75 cm, which were arranged such that they formed a 10 cm$\times$7.5 cm area. Horizontally this area safely overlapped the width of the pion beam (8 cm). However, vertically the foils intersected one third of the beam height (20 cm) at the target position of the EPICS spectrometer. Above and below the $^{48}$Ca target, oxygen-free iron and calcium foils enriched in $^{54}$Fe (97%) and $^{44}$Ca (95.4%) were placed. Data were accumulated on all three targets simultaneously. Software cuts using information on the point of scattering at the target (which is derived from the wire chambers located before the spectrometer dipoles) were used to separate events from the three targets. Unfortunately, the calcium metal had been converted to $Ca(OH)_2$ due to exposure to air prior to this experiment. The oxygen limited the energy resolution width to about 220 keV (FWHM). The calcium was isotopically enriched in $^{48}$Ca to 94.5%; its areal density was 106 mg/cm$^2$, not including the oxygen contamination. The energy resolution from the 100 mg/cm$^2$ thick, oxygen-free $^{54}$Fe target was about 150 keV (FWHM).

We took $(\pi^+,\pi^{+\prime})$ data at $T_\pi=116$ MeV and $(\pi^-,\pi^{-\prime})$ data at four energies between $T_\pi=116$ and 180 MeV at a momentum transfer $q=73$ MeV/$c$, where the $(\pi,\pi')$ differential cross sections are expected to have their maximum. The spectra for $^{48}$Ca + $\pi^\pm$ between 8 and 16 MeV in excitation energy, taken at $T_\pi=116$ MeV and $\theta_{lab}=20°$, are shown in Fig. 1. Almost all of the peaks in the spectra are due to oxygen. In addition, the oxygen worsens the signal to noise ratio for the $1^+$ state in $^{48}$Ca by decreasing the resolution and increasing the background.

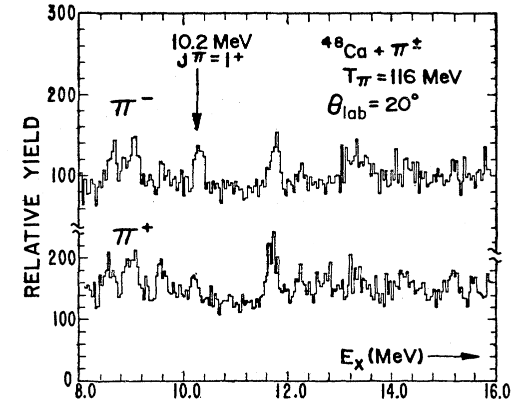


FIG. 1. Energy spectra for inelastic scattering of $\pi^+$ and $\pi^-$ from $^{48}$Ca at $T_\pi=116$ MeV and $\theta_{lab}=20°$ between 8.0 and 16.0 MeV excitation energy.

At 20° the 10.2-MeV state in $^{48}$Ca is not resolved from the 9.85-MeV state in $^{16}$O. Differential cross sections for the latter have been measured[29] at $\theta_{lab}\geq 30°$. We estimate a value $d\sigma/d\Omega=11\pm4$ $\mu$b/sr at $\theta_{lab}=20°$ based on these data and DWIA calculations.[29] Consequently, more than 50% of the weak $(\pi^+,\pi^{+\prime})$ peak at 10.2 MeV (Fig. 1) is due to the oxygen contamination. Due to these difficulties only an upper limit can be given for the $\pi^+$ cross section at $T_\pi=116$ MeV (Fig. 2).

In the (p,p′) (Refs. 13–16) and (e,e′) (Refs. 10 and 11) spectra the 10.2 MeV, $1^+$ state is much more prominent than in our $(\pi,\pi')$ spectra. This is expected on the basis of the very different nature of the forces responsible for

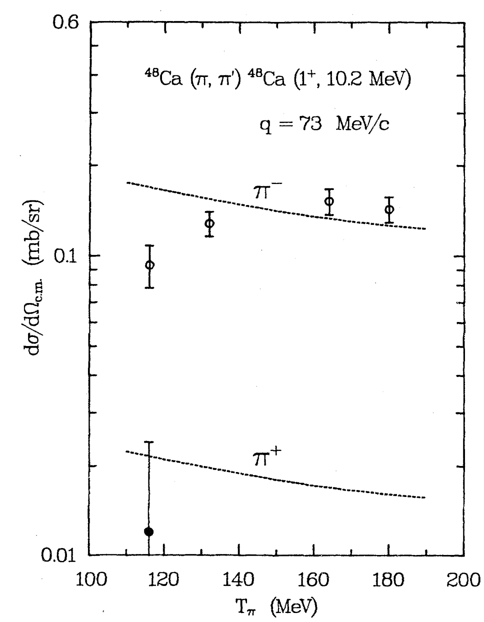


FIG. 2. Excitation functions measured at $q=73$ MeV/$c$ for inelastic scattering of $\pi^+$ (solid circles) and $\pi^-$ (open circles) from $^{48}$Ca to the $J^\pi=1^+$ state at 10.2 MeV excitation energy. Broken lines: results of DWIA calculations with spectroscopic amplitudes from Ref. 18, renormalized to fit the electron scattering cross sections of Ref. 10.

exciting this unnatural-parity state in these three reactions (see Sec. III).

There are several known states in $^{48}$Ca which are not resolved in our experiment. These states have been observed in high resolution $^{48}$Ca(p,p′) experiments[13,17] and were found to be relatively weakly excited at small momentum transfer. Although it is not very likely that states with $J>1$ are excited strongly in $(\pi,\pi')$ at this momentum transfer, we cannot exclude the possibility that the peak at 10.2 MeV excitation energy involves more than one state in $^{48}$Ca. It would be highly desirable to take $(\pi,\pi')$ angular distributions for the 10.2 MeV peak to unambiguously exclude contributions from transitions to $J>1$ states of natural parity. For the analysis of the data in Sec. III we assume the peak at 10.2 MeV (after subtraction of the oxygen contaminant) to be due to the $1^+$ state only.

Neither in the $^{54}$Fe nor in the $^{44}$Ca $(\pi,\pi')$ spectra was there any evidence for excitation of $1^+$ states. In the (e,e′) experiment[10,11] on these two nuclei the $M1$ strength was found to be distributed among many states, which makes their detection in $(\pi,\pi')$ experiments exceedingly time consuming with the presently available pion fluxes and energy resolution.

Absolute differential cross sections were obtained by normalization of the pion-hydrogen yields from a $CH_2$ target to calculated $\pi^{\pm}$-p cross sections using the pion-proton phase shifts of Ref. 30. The resulting excitation functions are presented in Fig. 2. The error bars in the figure represent statistics and uncertainties in background subtraction. They do not include an overall uncertainty in absolute normalization of $\pm 10\%$.

## III. DWIA ANALYSIS OF THE DATA

We have performed calculations in the distorted wave impulse approximation (DWIA) with the program ARPIN (Ref. 25) which uses the program PIPIT (Ref. 31) to calculate the distorted waves. The microscopic transition densities were obtained using harmonic oscillator wave functions and the shell-model one-body density matrix elements of Ref. 18. The oscillator parameter was chosen to be $b=2$ fm as in Ref. 16. The optical potential was generated from the pion-nucleon $t$ matrix as described in Ref. 31, and from the ground state density parameters derived from pion-calcium elastic scattering.[28] A two parameter Fermi shape, of half-density radius $c_{\rm p}=3.46$ fm for the protons and $c_{\rm n}=3.63$ fm for the neutrons, was employed. The diffusivity was $a=0.55$ fm for both protons and neutrons. The optical model fit to the elastic scattering data for $^{48}$Ca + $\pi$ of Ref. 28 is quite good with these parameters.

Transitions to unnatural-parity states must involve a spin transfer $\Delta S=1$ to the target. In pion scattering, spin transfer is induced by the pion-nucleon $LS$ force. This interaction is zero at $q=0$ and reaches its maximum at $q>2$ $\hbar$/fm for $T_\pi=180$ MeV (Ref. 32), where the transitions to high spin states have their peak cross sections. The $\Delta S=1$ transition to the $1^+$ state reaches its peak cross section at $q\simeq 0.37$ $\hbar$/fm, where the pion-nucleon $LS$ force is still relatively weak. In contrast, proton inelastic scattering can excite the $1^+$ state also by the central, spin-dependent force and the tensor force.[33] The isovector part of the former has a maximum at $q=0$ and is the main cause of the large (p,p′) cross section observed at small $q$. For example, $d\sigma/d\Omega_{\rm c.m.}=6$ mb/sr for (p,p′) at $T_{\rm p}=201$ MeV and $\theta_{\rm c.m.}=2°$ (Ref. 16), but for $(\pi^-,\pi^{-\prime})$ at $T_\pi=180$ MeV we find that $d\sigma/d\Omega_{\rm c.m.}$ is only $0.143\pm 0.014$ mb/sr at the peak of the angular distribution ($\theta_{\rm c.m.}=15°$).

The calculated differential cross sections at $q=0.37$ $\hbar$/fm$=73$ MeV/$c$ decrease with increasing energy when moving across the $\Delta_{3/2,3/2}$ (1232 MeV) resonance (Fig. 2). This behavior has been observed for many unnatural-parity transitions and was explained successfully in Ref. 34. However, the transition[26] to the $1^+,T=1$ state in $^{12}$C has shown an exception to this rule. The behavior of the experimental $\pi^-$ excitation function for $^{48}$Ca($1^+,T=4$,10.2 MeV) measured here is similar to the anomalous excitation function for the $^{12}$C($1^+$,15.1 MeV) $T_>$ state, but the rise of the differential $\pi^-$ cross section for $^{48}$Ca between $T_\pi=116$ and 180 MeV is not as steep as for the $^{12}$C. We note that the anomaly was not seen for the transition to the $^{12}$C($1^+$,12.71 MeV) $T_<$ state.

Since the transition from the $^{48}$Ca($0^+,T=4$,ground state) to the $^{48}$Ca($1^+,T=4$,10.2 MeV) state proceeds by an equal mixture of $\Delta T=0$ and $\Delta T=1$ components (if it is a pure neutron transition), a weaker signal in the excitation function for $^{48}$Ca is expected if the anomaly occurs only in the $\Delta T=1$ part of the transition density. Because we were not able to exclude unambiguously the possibility of contributions to the experimentally observed peak from weak transitions to natural-parity states, the rise in cross section with increasing pion energy may be due to the cross sections for natural-parity transitions which usually increase with increasing incident pion energy.[34]

## IV. DISCUSSION AND CONCLUSION

If we assume the data at $T_\pi=180$ MeV, i.e., "on resonance," to be due to a direct 1p-1h excitation, we can deduce spectroscopic amplitudes for comparison with the (e,e′) results. As already mentioned, all analyses of the data for the $(0^+,T=4)$ to $(1^+,T=4)$ transition in $^{48}$Ca assume a pure neutron excitation within the $1f2p$ shell. However, as long as only a single set of data, e.g., the form factor from (e,e′), is considered, that data set can in principle be interpreted also by a mixed neutron/proton transition. In isospin convention this would imply a $\Delta T=0$ amplitude different from the $\Delta T=1$ amplitude.

In Fig. 3 we have summarized the $\Delta T=0$ and $\Delta T=1$ amplitudes which are consistent with the two data sets, i.e., the $(\pi^-,\pi^{-\prime})$ absolute cross sections at $T_\pi=180$ MeV and the form factor from (e,e′). Shown in that figure is a graph of the isovector versus isoscalar rescaling factors $(1+\delta_1)$ and $(1+\delta_0)$, respectively, by which the $(1f2p)^{8n}_{0^+\to 1^+}$ shell model transition amplitudes of Ref. 18 need to be multiplied to reproduce the data. The solid lines within the shaded areas represent the rescaling factors for the $\Delta T=1$ and $\Delta T=0$ parts of the transition amplitudes which generate DWIA fits to the $(\pi^-,\pi^{-\prime})$ cross sections, and the (e,e′) form factor. The slope of the line

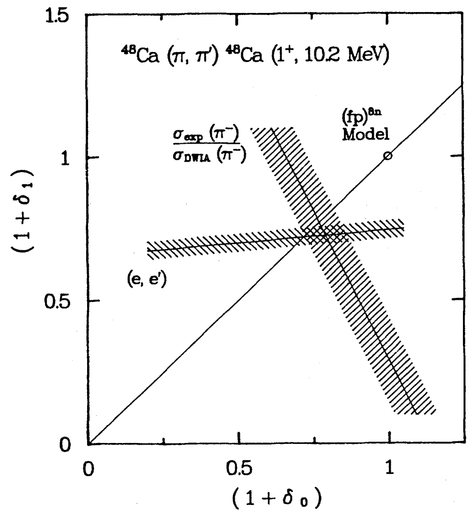


FIG. 3. Isovector $(1+\delta_1)$ versus isoscalar $(1+\delta_0)$ rescaling factors. Solid lines: values of $(1+\delta_1)$ and $(1+\delta_0)$ by which the amplitudes of Ref. 18 need to be multiplied to fit the $(\pi^-,\pi^{-\prime})$ cross sections at $T_\pi = 180$ MeV and the (e,e′) form factors. Shaded areas indicate the range of rescaling factors consistent with a variation of one standard deviation in the experimental cross sections. Diagonal line through the origin: factors which maintain a pure neutron transition.

for $(\pi^-,\pi^{-\prime})$ is $-2.1$, which is the ratio of the $\Delta T = 0$ over $\Delta T = 1$ parts of the pion-nucleon force according to the DWIA analysis of Sec. III. In the plane wave impulse approximation that ratio has the well-known value $-2.0$. The slope of the line for (e,e′) is close to zero since electrons are a nearly pure isovector probe of unnatural-parity transitions. Included in the calculations for (e,e′) which were done with the program ELEC (Ref. 35) are the (proton) current terms when $(1+\delta_0) \neq (1+\delta_1)$.

The shaded areas for $(\pi,\pi')$ and (e,e′) intersect near the line which indicates a pure neutron transition. Thus, the $^{48}$Ca$(\pi^-,\pi^{-\prime})$ data at $T_\pi = 180$ MeV are consistent with a pure neutron excitation and the quenching factor $(1+\delta_0)^2 = (1+\delta_1)^2 = 0.53$ which was deduced from $^{48}$Ca(e,e′)$^{48}$Ca.[10] However, since the DWIA calculations do not reproduce the energy dependence of the cross sections, it is not safe at present to extract nuclear transition amplitudes from these data. The main result of the present work is the observation of a second case of an anomalous $(\pi,\pi')$ excitation function. This anomaly is similar to the one found[26] in $^{12}$C$(\pi,\pi')^{12}$C$(1^+, T=1)$. It suggests a reaction mechanism which might involve a direct excitation of $\Delta N^{-1}$ components in the wave function of the $1^+$ states. A theoretical analysis of these data that goes beyond the standard DWIA calculation presented here is necessary. Also, reliable $\pi^+$ data need to be taken to allow a complete analysis of this important transition.

## ACKNOWLEDGMENTS

The authors are indebted to professor P. J. Ellis for valuable discussions and to Professor B. H. Wildenthal for supplying us with the transition density amplitudes. This work was supported in part by the United States Department of Energy, The Robert A. Welch Foundation, and the Japan-United States Cooperative Science Program.


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