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Pion inelastic scattering to low-lying states in ^{12}C and ^{40}Ca

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Pion inelastic scattering at 180 MeV from the low-lying collective states of ^{12}C and ^{40}Ca is analyzed using distorted-wave impulse approximation calculations with no free parameters and transition densities obtained from electron scattering. These calculations adequately reproduce the pion scattering data. No significant π^+ vs π^- differences are observed at low-momentum transfers.

[NUCLEAR REACTIONS: ^{12}C($\pi^{\pm}, \pi^{\pm\prime}$) and ^{40}Ca($\pi^{\pm}, \pi^{\pm\prime}$), E_π=180 MeV. Measured $\sigma(\theta)$, DWIA analysis, π^+ vs π^- comparisons.]

I. INTRODUCTION

Pion inelastic scattering is a valuable probe of nuclear structure because of its ability to separate neutron and proton contributions to transition densities in the region of the pion-nucleon $\{J=\frac{3}{2},\ T=\frac{3}{2}\}$ resonance. Calculations of inelastic scattering using transition densities based on shell-model wave functions often produced qualitative but *not* quantitative agreement with the data.[1,2] However, before stringent tests of neutron and proton amplitudes in the nuclear wave functions can be made, it is important to find out how well the reaction mechanism for pion-nucleus inelastic scattering is understood. One way to test our empirical model of the reaction mechanism is to compare calculations and data for transitions in which the transition densities are well known. Such a test case may be found in inelastic scattering to the low-lying collective states in self-conjugate nuclei such as ^{12}C and ^{40}Ca, where proton and neutron transition densities should be equal and the proton transition densities have been determined from electron and proton inelastic-scattering measurements.

The assumption that the neutron and proton transition densities are the same is valid only in the absence of isospin mixing. However, significant isospin-mixing effects in these low-lying collective states should be manifested, if present, in differences between the π^+ and π^- measurements. Although random phase approximation (RPA) wave functions of Gillet and Sanderson[3] predict the 3_1^- state in ^{40}Ca to be nearly pure $T=0$, they predict large $T=1$ admixtures in the 3_2^- and 3_3^- states, because of Coulomb-induced isospin mixing.

II. DATA ACQUISITION

The data were obtained using the Energetic Pion Channel and Spectrometer (EPICS) system at the Los Alamos Clinton P. Anderson Meson Physics Facility (LAMPF). The EPICS system, described elsewhere,[4] consists of a momentum-dispersing channel and a high-resolution spectrometer. Position-sensitive, delay-line read-out drift chambers[5] measure the particle trajectories, i.e., positions and angles, both before and after the spectrometer dipoles. For each event, an on-line computer program projects this trajectory back to the scattering target to reconstruct the scattering angle and incident momentum and calculates the scattered pion momentum to third order in the particle coordinates. A Q value for the reaction under study is calculated using these momenta and the scattering angle, and its value is histogrammed.

Data at angles larger than 20° were taken with a channel momentum bite of ±2%. For angles smaller than 20°, this was reduced to ±0.4% to lower the counting rate. The pion flux was approximately $10^8\ \pi^+/s$ and $2\times10^7\ \pi^-/s$ for the large momentum bite. This flux was monitored by an ion chamber located 75 cm downstream of the target. The ion chamber had a 3 cm graphite absorber in front of it to range out incident protons in the π^+ beam. The angular resolution of the beam was about 10 mrad for both momentum bite settings.

The data were taken with the full acceptance of the spectrometer of 10 msr. The range of scattering angle accepted by the spectrometer was $\pm 2°$. The momentum acceptance of the spectrometer was $\pm 6\%$, which allowed a 30 MeV region of excitation energy to be studied in one setting. This was sufficiently large so that one spectrometer setting could be used for all the angle settings.

Natural carbon and calcium targets of 100 mg/cm^2 areal density were used. The target dimensions were 15×22 cm. A 7% oxygen content (by number of atoms) in the calcium target was the only significant contaminant. The resolution obtained in the present experiment of 150 keV full width at half maximum (FWHM) was sufficient to separate the oxygen and calcium elastic-scattering peaks at all angles greater than 20°. At angles less than 20° this small contaminant was ignored.

A typical spectrum of pion scattering from ^{40}Ca is shown in Fig. 1. Here we present data for the 4.439 (2^+), 7.654 (0^+), 9.641 (3^-) MeV states in ^{12}C and for the 3.352 (0^+), 3.736 (3_1^-), 3.908 (2^+), 4.492 (5^-), 6.256 (3_2^-), 6.583 (3_3^-) MeV states in ^{40}Ca. Data on ^{12}C were obtained between laboratory scattering angles of 14° and 60°, and data on ^{40}Ca were obtained between 14° and 40°. Previous data[6] obtained on ^{40}Ca are also included in the present analysis. All data were obtained at a pion energy of 180 MeV. The present elastic and inelastic data are in good agreement with previous data taken for π^- scattering at 180 MeV from ^{12}C.[7]

III. DATA REDUCTION

Peak areas were extracted from the Q-value spectra using the program LOAF.[8] The peaks were fitted with a fixed line shape extracted from the elastic-scattering peak. The relative separations between peaks were constrained at values obtained

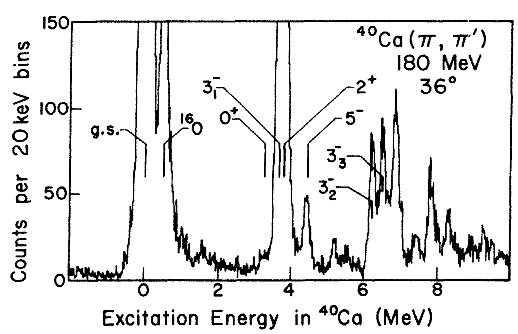

FIG. 1. A typical pion inelastic-scattering spectrum obtained on ^{40}Ca. The states of interest are labeled.

from the energy-level compilations.[9,10] This technique allowed the 0^+, 3^-, 2^+ triplets in ^{40}Ca to be reliably separated at all angles.

The data were normalized to π^+ and π^- scattering on hydrogen, using Coulomb-corrected phase-shift predictions with the phase shifts of Rowe, Salomon, and Landau.[11] The ratio of experimental yield to the predicted $\pi^+ + p$ cross sections was shown to be flat within $\pm 2\%$ in the angular region between 40° and 120°. The data were corrected for solid angle as a function of position along the focal plane, survival fraction through the spectrometer, chamber efficiency, and computer live time. The correction for solid angle was measured by mapping the focal plane using inelastic scattering from the 2^+ (4.439 MeV) state of ^{12}C at an angle of 35° corresponding to the first maximum in its angular distribution. Chamber efficiency and computer live times were monitored on line. The forward-angle ($\theta \leq 20°$) data were normalized to the backward angle data ($\theta \geq 20°$) by running overlap points at 20°.

Estimated systematic errors in the data set include: normalization error $\pm 3\%$, focal-plane variation of solid-angle $\pm 2\%$, peak-shape fitting errors $\pm 5\%$, survival fraction correction $\pm 3\%$, chamber efficiency $\pm 3\%$, and beam monitoring $+3\%$. This gives an overall normalization uncertainty of $\pm 9\%$ and a relative π^+ vs π^- uncertainty of $\pm 6\%$. Since the chamber efficiencies are a function of angle (because of count-rate variations), this may introduce systematic angle-dependent errors on the order of $\pm 3\%$.

IV. DWIA ANALYSIS

The data and the results of distorted wave impulse approximation (DWIA) calculations are shown in Figs. 2–5. For these DWIA calculations, the coordinate-space code DWPI[12] was used. All calculations incorporated the Kisslinger[13] form for the optical-model potential

$$2EV(\boldsymbol{r}) = -b_0 k_\pi^2 \rho(\boldsymbol{r}) + b_1 \vec{\nabla} \cdot \rho(\boldsymbol{r}) \vec{\nabla} \, ,$$

where $\rho(r)$ is obtained by unfolding the proton charge distribution from the nuclear charge distribution as determined from electron scattering.[14] Here, b_0 and b_1 are related to the π-nucleon scattering amplitudes and k_π is the pion momentum. We have examined the effect on the inelastic scattering of two previously used schemes[15,16] of evaluating b_0 and b_1, because the kinematics used in those evaluations are ambiguous. The results of these two calculations are shown in Fig. 2. Although there are large differences in the elastic-scattering calculations, particularly in the region of the minima, we see only a 10% effect on the in-

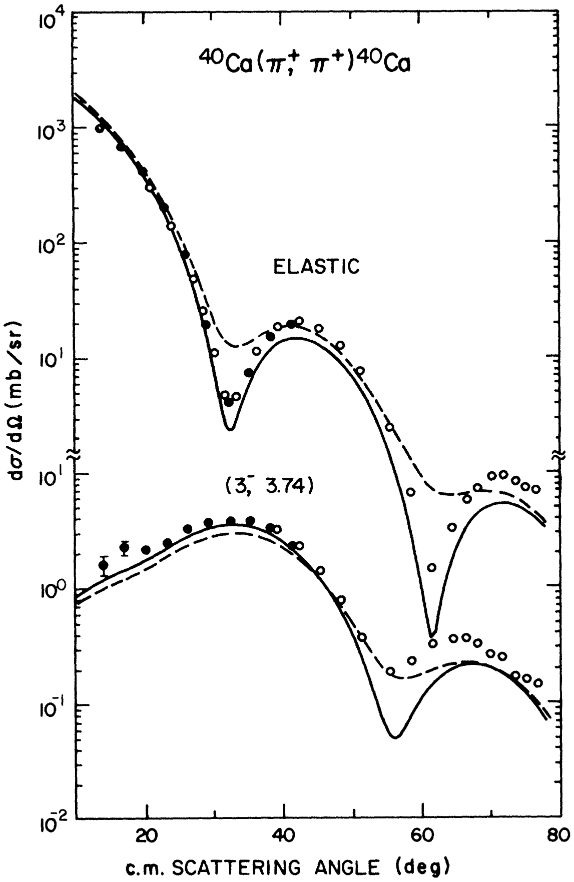

FIG. 2. The effects of two different models used to evaluate the potential parameters b_0 and b_1. The dashed curve was obtained using the method of Ref. 15 and the solid curve was obtained using the method of Ref. 16. The solid data points are the present data, whereas the open circular data points are from Ref. 6.

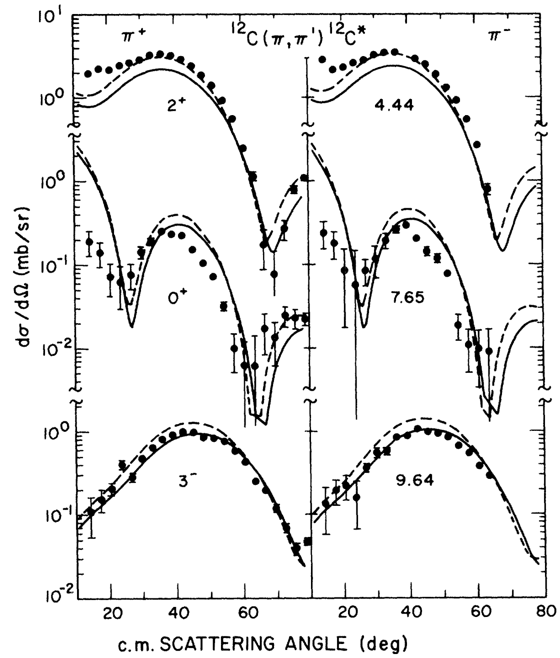

FIG. 3. Data and calculations for ^{12}C. All transition densities were obtained from Ref. 20 and are of the shell-model type. For the 2^+ (4.439 MeV) and 3^- (9.641 MeV) states the solid curve uses transitions deduced from the wave functions of Ref. 21. All others are empirical.

elastic scattering at the forward maximum. For the remaining calculation, we use the prescription from Holtkamp and Cottingame.[16] This prescription was shown to give good fits to previous elastic scattering data from both ^{12}C (Refs. 7, 17) and ^{40}Ca (Refs. 18, 19) at energies between 120 and 280 MeV with only one free parameter, an energy shift used in evaluating the π-nucleon t matrix of about −30 MeV.

V. ^{12}C CALCULATIONS

For scattering to the 2^+ (4.439 MeV), 0^+ (7.654 MeV), and 3^- (9.641 MeV) states in ^{12}C, an analysis of proton inelastic scattering at 1 GeV was performed by Gustafsson and Lambert[20] using both RPA shell-model transition densities[21] and empirical shell-model transition densities obtained by fitting electron-scattering data. Here we use those transition densities [neglecting the spin-dependent parts that were shown to have a small effect[22] in (π,π') to natural-parity states] to calculate pion inelastic-scattering cross sections for these same states. The results and are shown in Fig. 3.

Figure 3 shows that the general agreement between the calculations and the data is good, but there are some discrepancies. The first is the disagreement between calculations (using both transition densities) and the low-momentum-transfer data for scattering to the 2^+ (4.439 MeV) state. A similar disagreement was noted previously and ascribed to the effects of delta propagation through the nucleus.[23]

Also, although the general oscillatory pattern of the cross section to the 0^+ (7.654 MeV) state is reproduced by these calculations, the amplitude of these oscillations is overpredicted. This may be due to the strong coupled-channel effects for the excitation of this state noted previously by Sparrow and Gerace.[24]

VI. ^{40}Ca CALCULATIONS

For ^{40}Ca calculations, we used three different transition densities for the 3_1^- (3.736 MeV) and 2^+

(3.908 MeV) states: (1) collective-model transition densities obtained from fits to 800 MeV (p,p') data,[25] (2) empirical shell-model transition densities obtained from fits to (e,e') data,[26] and (3) Tassie-model transition densities from fits to (e,e') data.[27] For the high-lying states, the only analyses available are (1) and (2).

The data and calculations are presented in Figs. 4 and 5. The agreement is generally good, with the transition densities from electron scattering being somewhat better than the collective-model transition densities. Some differences are seen between π^+ and π^- at larger momentum transfer, in the region of the second maximum for the 3^- states; but at low momentum transfer the amplitudes and shapes of the angular distributions are well fitted for both π^+ and π^- scattering, with the assumption of an isoscalar transition density. No evidence is seen for the predicted isovector components[3] in the 3_2^- (6.256 MeV) and 3_3^- (6.583 MeV) states.

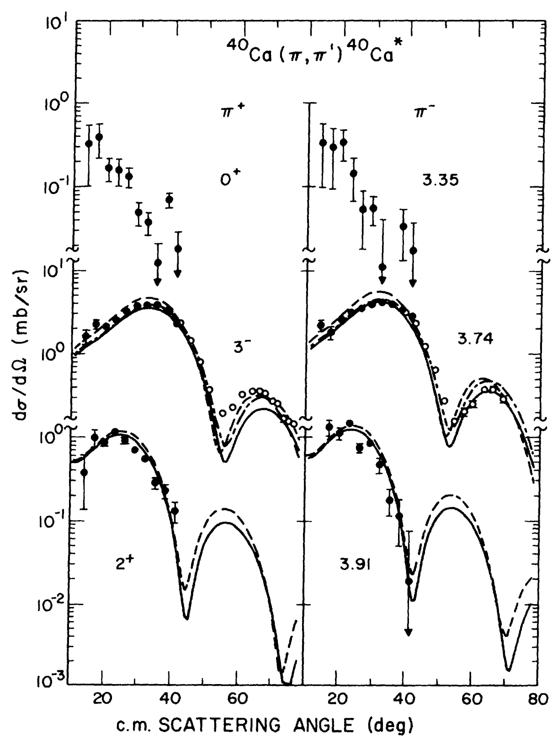

FIG. 4. Data and calculations for ^{40}Ca. Transition densities used for the calculations are continuous curves for the collective model of Ref. 25, dashed curves for the shell model of Ref. 26, and dot-dashed curves for the Tassie model of Ref. 27. The solid data points are the present data, whereas the open circular data points are from Ref. 6.

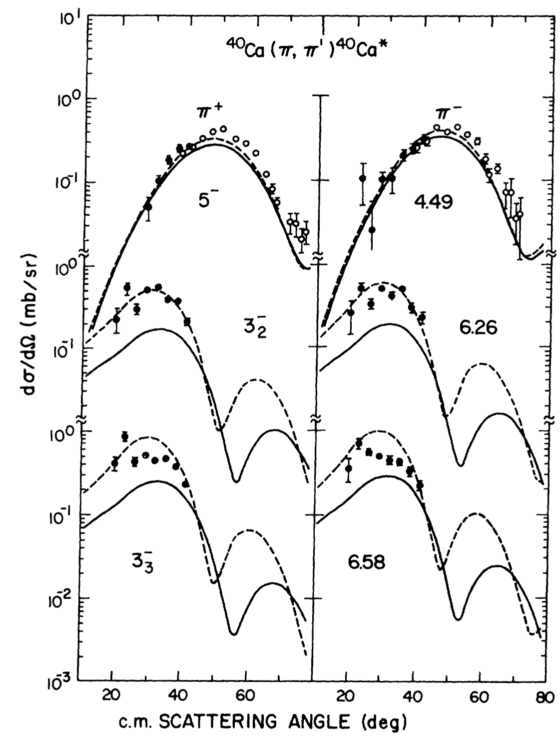

FIG. 5. Data and calculations for ^{40}Ca. Transition densities used for the calculations are continuous curves for the collective model of Ref. 25, dashed curves for the shell model of Ref. 26, and dot-dashed curves for the Tassie model of Ref. 27. The solid data points are the present data, whereas the open circular data points are from Ref. 6.

VII. CONCLUSION

DWIA calculations using empirical transition densities obtained from electron-scattering data give excellent agreement with these inelastic pion-scattering data from both ^{12}C and ^{40}Ca. Exceptions are seen for the 0^+ (7.654 MeV) state in ^{12}C, where the disagreements are probably due to coupled-channel effects, and for the low-momentum transfer to the 2^+ (4.439 MeV) state in ^{12}C where delta-propagation effects might be the cause. No significant differences between π^+ and π^- angular distributions are observed at forward scattering angles.

The good agreement between the present data and calculations and the π^+/π^- cross-section ratios of unity for these isoscalar states, using a model with no free parameters, indicate that our understanding of the reaction mechanism is good. This, along with the recent observation of $\pi^+/\pi^-\{\pi^-/\pi^+\}$ cross-section ratios of $9:1$ $\{1:9\}$ expected for pure proton $\{$neutron$\}$ states,[28,29] shows that pion inelastic scattering is a reliable method of determing the relative proton and neutron transition densities for exciting nuclear states. More importantly, such comparative measurements will add significantly to our understanding of nuclear structure.

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