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I. INTRODUCTION

This report summarizes the work carried out by The University of Texas at Austin at the Los Alamos Clinton P. Anderson Meson Physics Facility (LAMPF) during the period 1 April 1979 to 31 March 1980, under contract DE-AS05-76ER05224 between The University of Texas at Austin and the United States Department of Energy.

One of our faculty members was on site at LAMPF during each of the spring and fall semesters, and both were on site during the summer period. Seven graduate students were associated with the program, most being in residence at LAMPF the entire year. One technical support person was also on site during most of this period.

The research activities involved experiments done with the Energetic Pion Channel and Spectrometer (EPICS) and the External Proton Beam (EPB). Highlights of this research are included in this report.

The research cited in this report is, in many cases, the collaborative effort of many groups associated with research at LAMPF. Collaboration with LASL, Northwestern, Colorado,

Virginia, Minnesota, New Mexico State, and Florida A & M is acknowledged.

Two PhD's were granted by The University of Texas at Austin during this contract period based on experimental research done at LAMPF, bringing the total number of PhD's granted to Texas students in medium energy physics to five. Dr. Richard J. Joseph is presently an assistant professor at the Air Force Academy in Colorado Springs and Dr. David B. Holtkamp is a post-doc with the Minnesota group here at LAMPF.

II. RESEARCH WITH THE ENERGERIC PION CHANNEL AND SPECTROMETER
(EPICS)

A. Pion Double Charge Exchange (Texas, NMSU, and LASL)

Pion Double Charge Exchange (DCX) first excited interest in the early 1960's, since which time it has inspired considerable theoretical effort.¹⁻⁶ Pions comprise an isobaric triplet ($T_z = -1, 0, +1$) and, therefore, can excite Double Isobaric Analog States (DIAS). In a simple example of a double isobaric analog transition, $^{18}O(\pi^+, \pi^-)^{18}Ne$, the pion undergoes a double charge exchange with the two valence neutrons outside the closed nuclear core. In first order, DCX proceeds by a simple two-step mechanism whereby the valence neutrons would undergo sequential charge exchange passing through an intermediate Isobaric Analog State with little or no intrusion on the part of the closed core. In this model of DCX, the cross-section is particularly sensitive to correlations between the valence nucleons. Some calculations have indicated the process to be more complicated and strongly dependent on details of the nuclear structure, the nuclear surface, and the reaction mechanism.^{4, 6, 7, 8}

The targets, $^{16,18}\text{O}$, were chosen for study in light of extensive theoretical and experimental DCX treatments previously made with them. The nucleus ^{18}O is a particularly interesting target because the (π^+, π^-) reaction leads to a double isobaric analog state in the ground state of ^{18}Ne . Comparison with DCX on the closed shell nucleus, ^{16}O , should offer some insight into the relative strengths of isobaric analog versus non-isobaric analog transitions. Another pair of targets, $^{24,26}\text{Mg}$, were chosen likewise because of the possible DIAS transition in ^{26}Mg and its nonexistence in ^{24}Mg . Systematic effects in the DCX reaction may be looked for when the Oxygen pair is compared to the Magnesium pair.

Throughout the 1960's, attempts were made to isolate two-body final states formed in the DCX reaction.^{9,10,11} The limited capabilities, notably poor resolution and low pion flux, of the existing experimental facilities obliterated any structure in the data and only upper limits were established on DCX cross-sections for a few nuclei. In recent years experiments performed at LAMPF, SIN, and TRIUMF observed these elusive transitions, but continued poor resolution prevented an unambiguous identification of these much sought-after final states.

During the summer of 1979, a Texas - New Mexico - LASL collaboration redesigned EPICS to allow measurements of (π^+ , π^-) scattering at far forward angles (5° - 35° in the lab). A circular bending magnet positioned after the scattering target selected pions with an opposite polarity from that of the incident pion beam. This magnet eliminated most of the particles with the wrong sign of charge, tremendously reducing counting rates in the spectrometer's entrance drift chamber. The scattering chamber was redesigned to enable vacuum coupling between the target and the spectrometer, resulting in a substantial improvement in resolution (≤ 150 keV).

The experiment measured the energy excitation function of the four nuclei, $^{16,18}\text{O}$ and $^{24,26}\text{Mg}$, at 5° and a range of pion energies extending from ~ 80 to ~ 300 MeV. Angular distributions were taken using ^{18}O at 164 MeV and 292 MeV, and using ^{26}Mg at 292 MeV for $5^\circ < \theta < 35^\circ$. The larger-angle ^{18}O data taken at 164 MeV are in agreement with a previous measurement made by K. K. Seth,¹² which was taken with the EPICS spectrometer operating in its ordinary mode.

Peaks were observed for both the double isobaric analog state (g.s., 0^+) and the first excited state (1.88 MeV, 2^+) in ^{18}Ne (Figure 1). Figure 2 is an angular distribution for

$^{18}\text{O}(\pi^+, \pi^-)^{18}\text{Ne}$ (g.s., DIAS) at an incident pion energy of 164 MeV and 291 MeV. Figure 3 is an excitation function for both $^{18}\text{O}(\pi^+, \pi^-)^{18}\text{Ne}$ (g.s.) and $^{16}\text{O}(\pi^+, \pi^-)^{16}\text{Ne}$ (g.s.), at $\theta_{\text{lab}} = 5^\circ$. The excitation function for ^{18}O rises to a local maximum around 120 MeV and exhibits a minimum in the vicinity of the (3,3) resonance. This is the first excitation-function measurement of DCX across the (3,3) π -nucleon resonance. The excitation function for ^{16}O has a dramatically different behavior from that of ^{18}O in that it continues to fall as the incident pion energy is increased beyond resonance.

Johnson¹³ calculates that in the region of the (3,3) resonance, angular distributions of DCX transitions involving double isobaric analog states are sensitive to differences in the neutron and proton compositions of the nuclear surface. The angular distributions should appear diffractive in nature characterized by a nuclear radius \bar{R} marking the 10-20% density point and giving a zero in $J_0(q\bar{R})$, where q is the momentum transfer. As seen by Seth¹² at 164 MeV, the minimum in the ^{18}O angular distribution at 164 MeV is located at too small an angle (20° - 25°) to reproduce the accepted strong absorption radius — it would be far too large. However, the ^{18}O angular distribution at 292 MeV (see Figure 2), with a minimum slightly greater in angle than at 164 MeV, is consistent with the diffractive

behavior of a nucleus the size of ^{18}O . These data suggest the double isobaric analog transition is more dominant at 292 MeV than at 164 MeV.

A coinciding study conducted on the pair $^{24,26}\text{Mg}$ (Figures 4 and 5) shows striking similarities to $^{16,18}\text{O}$, the only immediate difference being the relative magnitudes of the excitation functions. As in the ^{18}O data, the 292 MeV angular distribution of ^{26}Mg , with a minimum around 28° , is consistent with the expected nuclear size.

In summary, transitions to the Double Isobaric Analog State (DIAS) appear to dominate the reaction mechanism at incident pion energies substantially above the (3,3) resonance, e.g. 291 MeV. This conclusion rests on two bodies of data: (1) In Oxygen and Magnesium at 5° , the cross section for a transition to a DIAS is 20 to 100 times stronger than the non-analog transitions, and (2) Near 291 MeV, angular distributions from targets of ^{18}O and ^{26}Mg are each consistent with a simple diffraction shape using appropriate strong absorption radii.

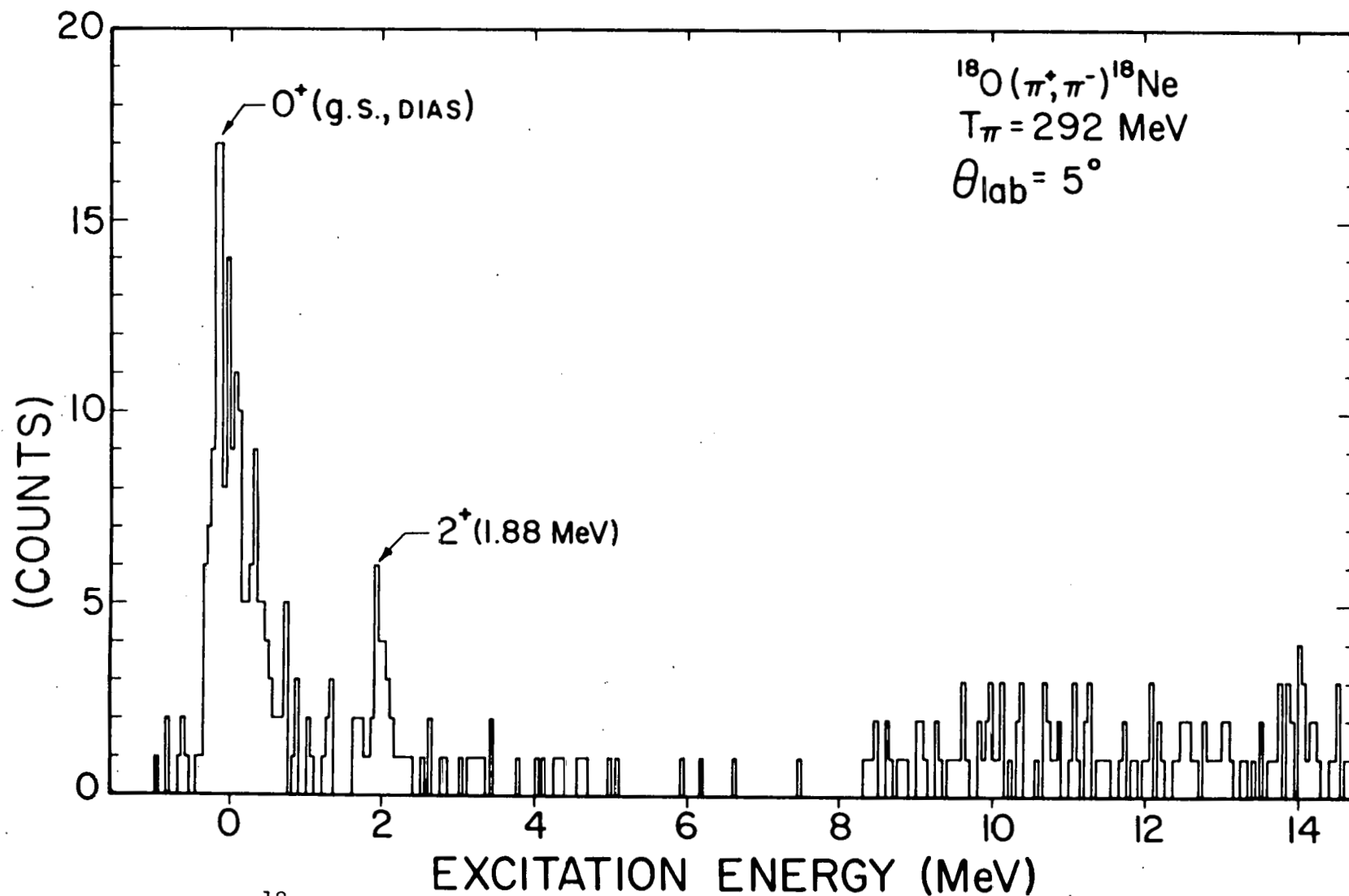


Figure 1. ^{18}Ne spectra showing the Double Isobaric Analog State (g. s. 0^+) and the first excited state (1.88 MeV 2^+).

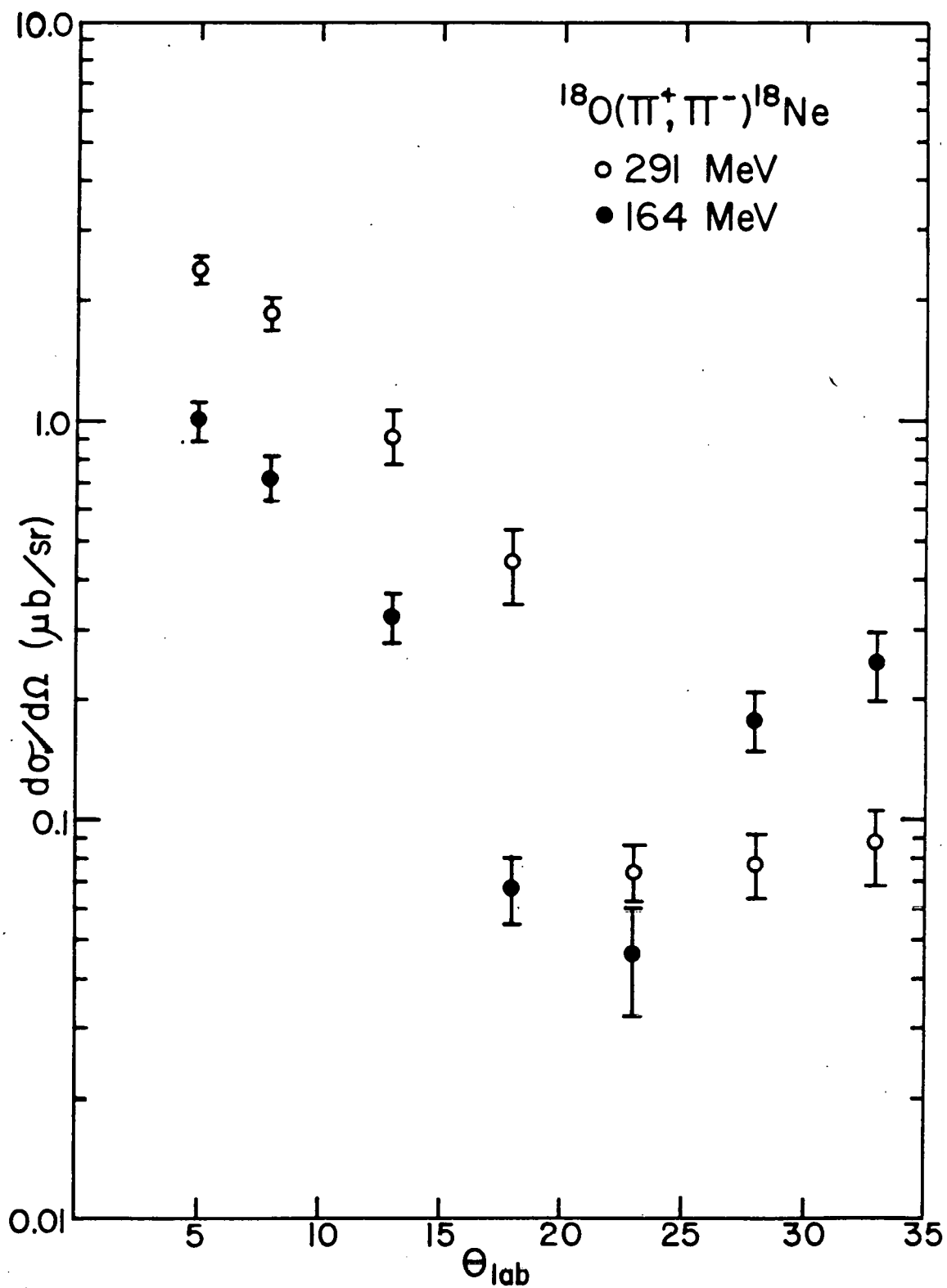


Figure 2. Angular distribution of the excitation function for the reaction, $^{18}\text{O}(\pi^+, \pi^-)^{18}\text{Ne}$, at an incident energy of 291 and 164 MeV.

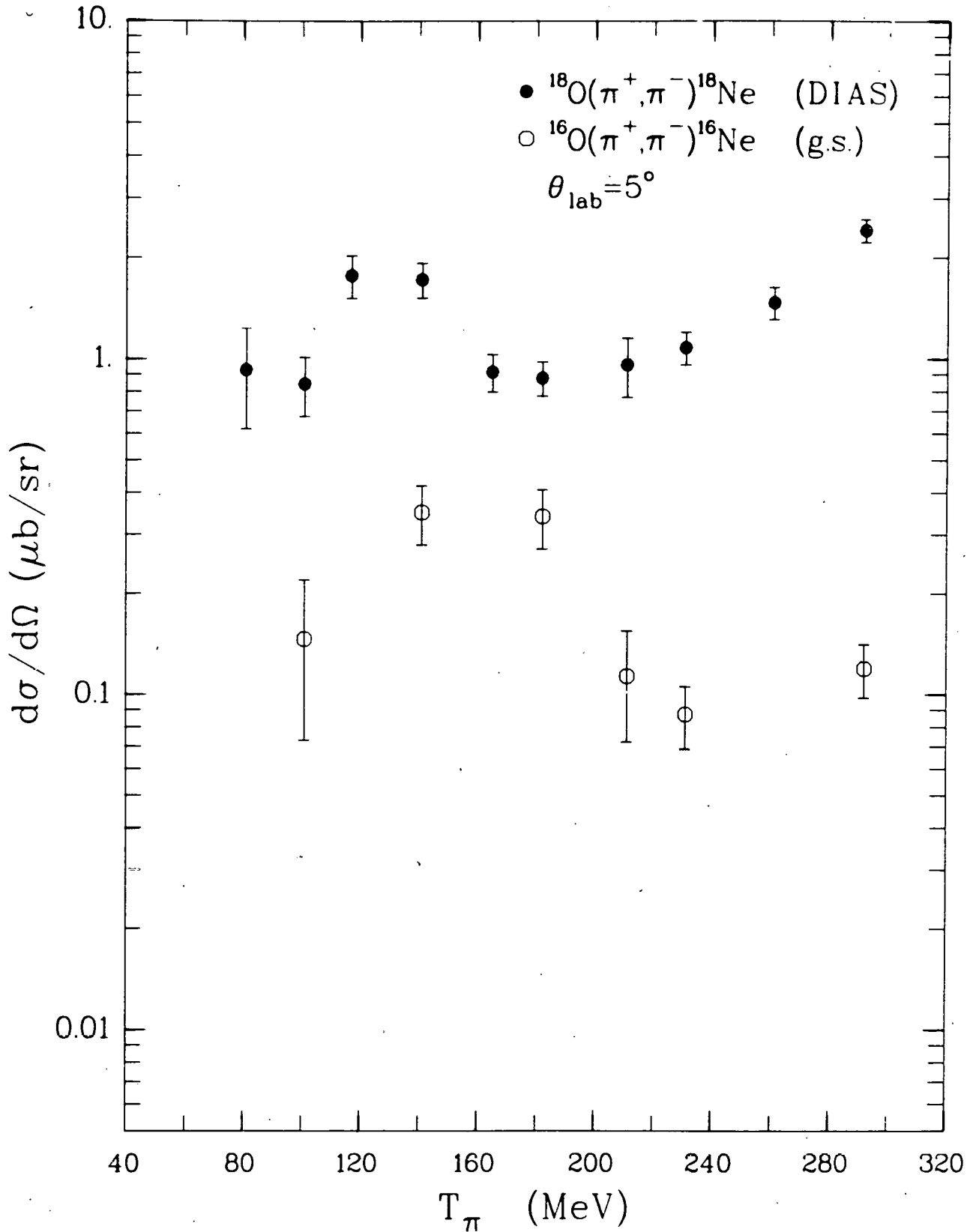


Figure 3. Excitation function for $^{18}\text{O}(\pi^+, \pi^-)^{18}\text{Ne}$ (g. s.) and $^{16}\text{O}(\pi^+, \pi^-)^{16}\text{Ne}$ (g. s.) at $\theta_{\text{lab}} = 5^\circ$.

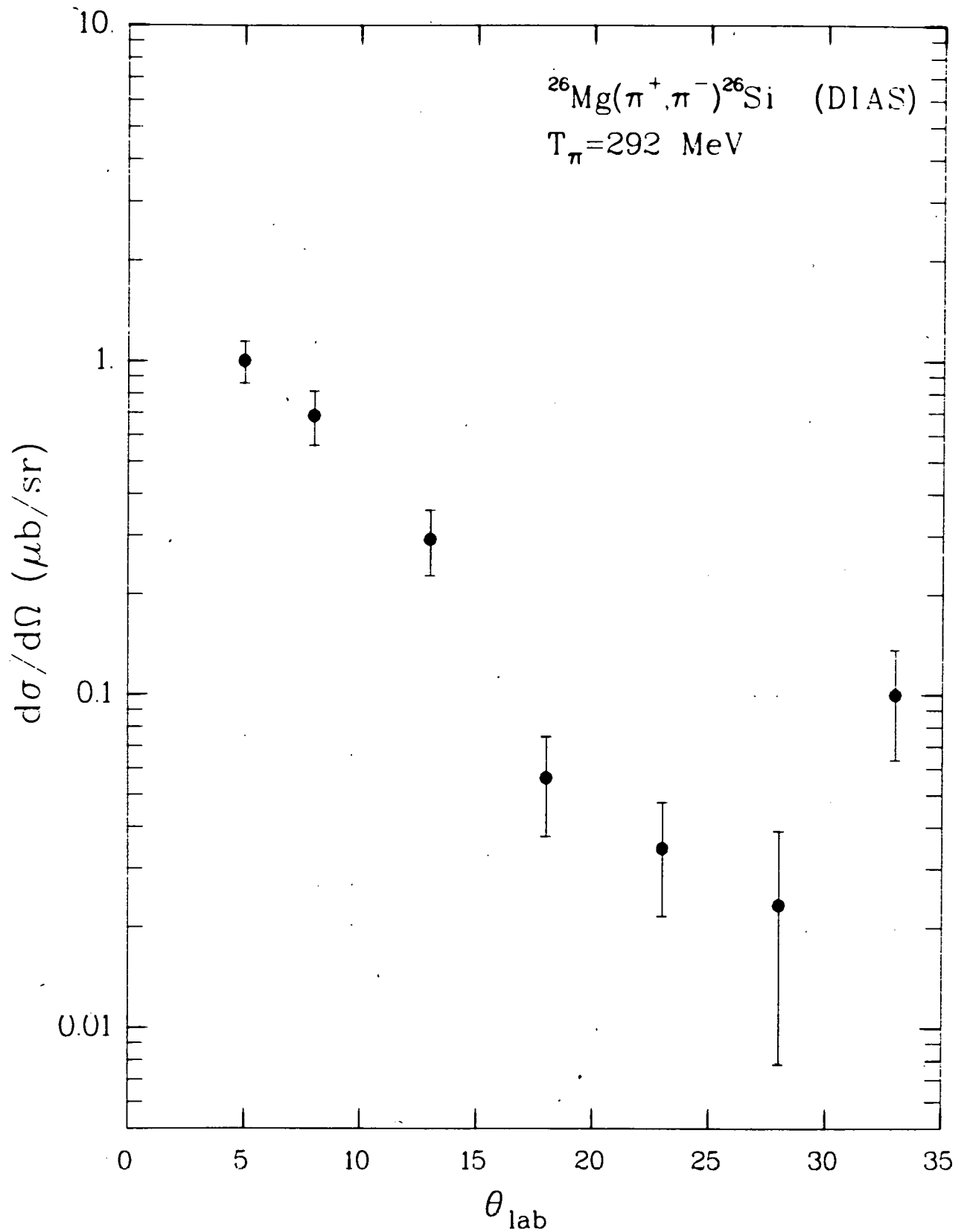


Figure 4. Angular distribution of the excitation function for the reaction $^{26}\text{Mg}(\pi^+, \pi^-)^{26}\text{Si}$ for an incident pion energy of 292 MeV.

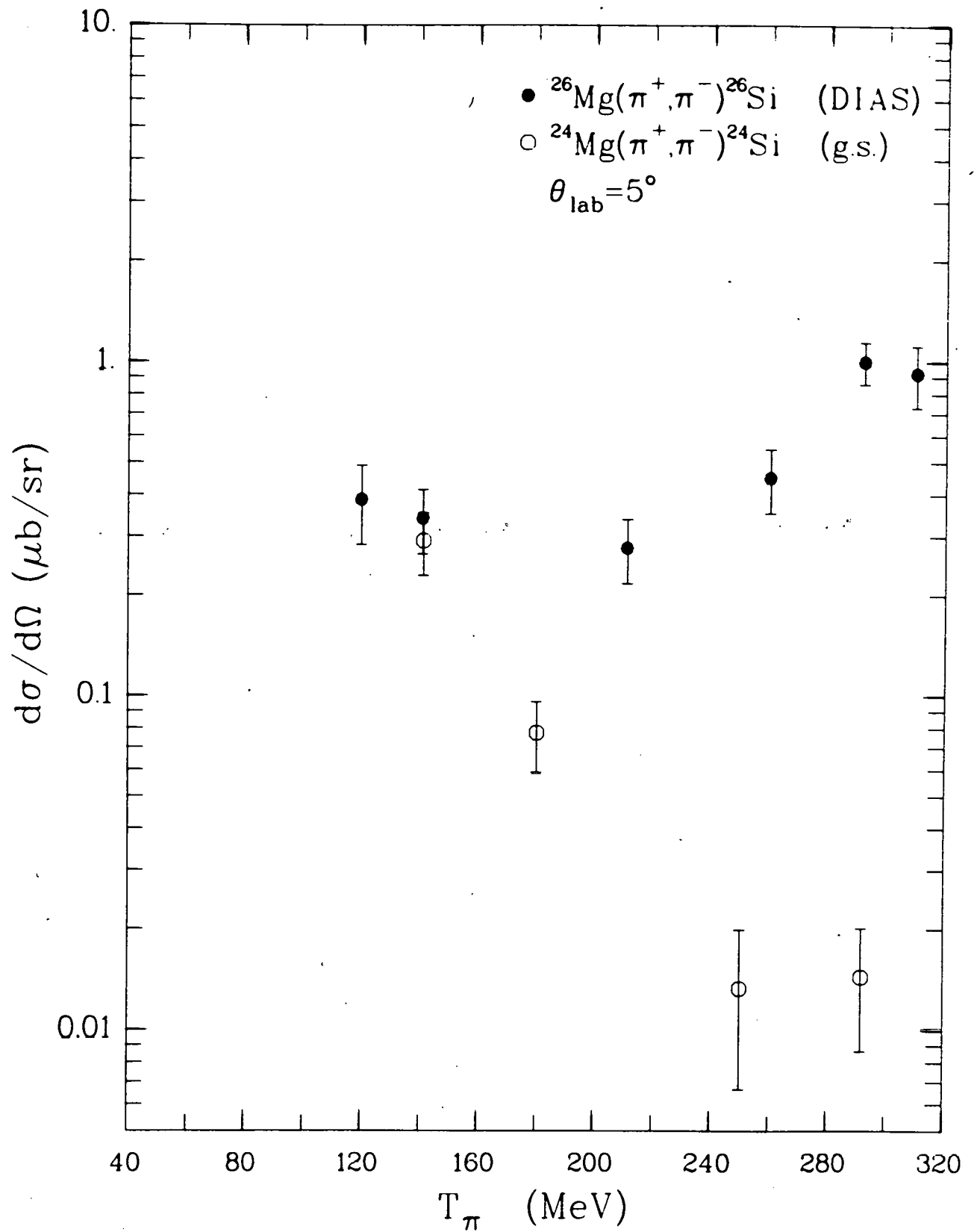


Figure 5. Excitation function for $^{26}\text{Mg}(\pi^+, \pi^-)^{26}\text{Si}$ and $^{24}\text{Mg}(\pi^+, \pi^-)^{24}\text{Si}$ at $\theta_{\text{lab}} = 5^\circ$.

B. Isospin Mixing in ^{12}C and ^{16}O

The coexistence of two isospin eigenvalues discovered in doublets of nuclear states has brought up the possibility of measuring charge dependence in the strong interaction using selected nuclear reactions. The size of the off-diagonal, charge dependent matrix element, H_{10} , between the two states may not be fully accounted for by residual Coulomb interactions. In previous work, the only three documented cases of isospin mixing between two distinct nuclear states are: the almost maximally mixed 2^+ states in ^8Be near 16.5 MeV,^{14,15} the partially mixed 1^+ states in ^{12}C at 12.7 and 15.1 MeV,^{16,17,18} and the 2^- states in ^{16}O around 13 MeV.¹⁹

i. ^{12}C (Texas, LASL)

Measured values for the off-diagonal, charge-dependent matrix elements for ^{12}C vary roughly from 100 keV to 300 keV. Calculations of residual, two-body Coulomb matrix elements generally yield values less than 100 keV although more recent calculations by Sato and Zamick,²⁰ Lawson,²¹ and Barker²² have produced values ranging from 60 to 240 keV.

Comparison of π^+ to π^- inelastic scattering for pairs of isospin-mixed states in self-conjugate nuclei is a new method to measure isospin mixing. When two nuclear states are sufficiently close in energy so that the two state theorem applies, the wavefunctions of the two states can be written as:

$$|A\rangle = \alpha|0\rangle - \beta|1\rangle,$$

$$|B\rangle = \alpha|1\rangle + \beta|0\rangle$$

with $\alpha^2 + \beta^2 = 1$. The charge dependent matrix element is then given by:

$$H_{10} = \frac{\alpha\beta(E_1 - E_0)}{(\alpha^2 - \beta^2)},$$

with E_0 and E_1 being the unperturbed energies of the T=0 and T=1 states, respectively.

Transforming to a particle-hole basis, the two states become:

$$|A\rangle = \frac{1}{\sqrt{2}}\{(\alpha - \beta)|nn^{-1}\rangle + (\alpha + \beta)|pp^{-1}\rangle\},$$

$$|B\rangle = \frac{1}{\sqrt{2}}\{(\alpha+\beta)|nn^{-1}\rangle - (\alpha-\beta)|pp^{-1}\rangle\}.$$

Using the amplitude ratio of 3:1 for $\pi^+ + p : \pi^- + p$ and $\pi^- + n : \pi^+ + n$ for pion-nucleon scattering on the (3,3) resonance, one can obtain the following ratios:

$$\frac{\sigma_A^{\pi^+}}{\sigma_B^{\pi^+}} = |(2\alpha+\beta)/(\alpha-2\beta)|^2$$

$$\frac{\sigma_A^{\pi^+}}{\sigma_A^{\pi^-}} = |(2\alpha+\beta)/(2\alpha-\beta)|^2$$

$$\frac{\sigma_B^{\pi^+}}{\sigma_B^{\pi^-}} = |(\alpha-2\beta)/(\alpha+2\beta)|^2$$

In the case of no isospin impurities ($\alpha=1, \beta=0$), the cross-section ratio for populating the T=0 state |A> versus populating the T=1 state |B> is 4:1 while the π^+ to π^- ratios for each are unity. Positive and negative pions are scattered equally by eigenstates of isospin. At maximal mixing ($\alpha = \beta = 1/\sqrt{2}$), |A> becomes a pure proton state and |B> becomes a pure neutron state. A proton state has three times the amplitude for scattering π^+ than does a neutron state and the reverse holds true for π^- . As a consequence, for maximal mixing, the π^+ to π^- cross-section ratios become 9:1 for scattering to state |A> and 1:9 for scattering to state |B> as in free π -nucleon scattering. These

simple calculations indicate the usefulness of pions as a tool for discovering isospin mixing in $T_z = 0$ nuclei.

Figure 6 demonstrates σ^{π^+} and σ^{π^-} spectra for pion inelastic scattering from ^{12}C at 162 MeV. The most striking feature of pion scattering at high momentum transfer is the strong excitation of a group of states near 19.5 MeV. The difference spectrum $\{\sigma(\pi^-) - \sigma(\pi^+)\}$, inset exhibits a strong bipolar peak around 19.5 MeV, exactly what one would expect in the case of strong isospin mixing. A proton state present at 19.25 MeV is seen clearly only with π^+ and a neutron state at 19.65 MeV is seen only with π^- . Contributions from states of pure isospin subtract to zero within statistical errors. Calibration of the EPICS system using the 4^- states of ^{16}O at 17.79, 18.98, and 19.80 MeV insure that the energy of the 19.25 MeV state in ^{12}C is known to $\pm .05$ MeV (standard deviation) and that the separation of the two states is known to $\pm .04$ MeV.

Some time ago, Siciliano²³ suggested that the 19.5 MeV group was the long sought 4^- , $T=0$ ($p_{3/2}^-$, $d_{5/2}^-$) stretched state and the measured angular distribution for π^+ scattering is consistent with this interpretation. However, the strongest argument for the 4^- assignment comes from 180° electron scattering.²⁴ From the present data we conservatively estimate the $\sigma^{\pi^+}/\sigma^{\pi^-}$ to be

greater than 2:1 for the 19.25 MeV state and less than 1:2 for the 19.65 MeV state. Applying the two-state mixing theorem to the ratios obtained for the lower state and assuming that the physical overlap between the two states can be neglected gives $\beta > 0.32$ and $H_{10} > 120$ keV.

Recent proton transfer data from Colorado (J. Shepard, *et al.*²⁵), using the $^{11}\text{B}(^3\text{He},d)^{12}\text{C}$ reaction, indicates $\ell=2$ strength in the 19.25 MeV region which is consistent with two aspects of our present work: (1) our identification of the 4^- state as the stretched configuration $|p_{3/2}^{-1}, d_{5/2}\rangle$ is consistent with $\ell=2$ strength seen in the proton transfer data, and (2) our measurement of a very strong inelastic π^+ enhancement of the 19.25 MeV state, indicating this state to be a nearly-pure proton particle-hole state, is consistent with proton-stripping having significant strength at 19.25 MeV excitation.

An examination of the π^+ and π^- data at small momentum transfer (25° , 180 MeV) turns up another pair of isospin mixed states in ^{12}C . A state 500 keV in width appears strongly at 18.35 MeV in the π^+ data. In the π^- data the 18.35 MeV peak is greatly diminished while a 19.35 MeV peak appears. We associate the 19.35 MeV state as the 2^- , $T=1$ state identified in electron scattering and the 18.35 MeV state as its partially isospin-mixed

2^- , T=0 partner (Figure 7). A minimum estimate of the isospin-mixing matrix element for the 2^- doublet is 200 keV using the two-state formulation described above.

An off-diagonal, charge dependent matrix element of $H_{10} = 134 \pm 43$ keV has been extracted for the partially mixed 1^+ doublet of states at 12.7 and 15.1 MeV, using the new method of comparing π^+ versus π^- inelastic scattering. This result is in substantial agreement with the recent electromagnetic measurement of $H_{10} = 110 \pm 30$ keV reported by Adelburger, et al.¹⁶ and the recent nuclear-reaction based measurement of $H_{10} = 179 \pm 70$ keV reported by Lind, et al.¹⁸ Figure 8 is an energy spectrum for both π^+ and π^- inelastic scattering from ^{12}C , where the solid lines are the best fit to the peaks at 12.7 and 15.1 MeV using experimentally-determined line shapes.

ii. ^{16}O (Texas, Minnesota, LASL)

A study of ^{16}O at large momentum transfers was carried out at EPICS using pions of both charged species which were incident on ice targets (160 and 320 mg/cm^2 thickness) formed and contained between 1 mil copper foils, which were cooled with conventional refrigeration units to a temperature of -60°C . The

incident pion energy was chosen to be 164 MeV, and the angular range was from 45° to 89° (lab). Standard EPICS spectrometer and channel settings were used with the addition of a 27.9 cm slab of graphite in the focal plane of the spectrometer followed by a veto scintillator. This veto rejected muons which resulted from the decay of pions in flight at the front of the spectrometer. Typical energy resolution ranged from 300 to 400 keV (FWHM).

Spectra obtained from π^+ and π^- scattering at a lab angle of 77° are shown in Figure 9. A number of inelastic states are resolved in ^{16}O , among them are three states near 19 MeV, which exhibit large π^+/π^- asymmetries in the cross sections for excitation of the (4^- , $T=0$) states. From the angular distributions one may obtain the following ratios of the yields for π^+ vs. π^- , averaged over the angular range in which these states were visible ($53^\circ \leq \theta_{\text{lab}} \leq 89^\circ$): (1) 17.79 MeV (4^- , $T=0$), $R(\pi^+/\pi^-) = 1.62 \pm 0.14$; (2) 18.98 MeV (4^- , $T=1$), $R(\pi^+/\pi^-) = 0.974 \pm 0.081$; and (3) 19.80 MeV (4^- , $T=0$), $R(\pi^+/\pi^-) = 0.595 \pm 0.074$. At an incident pion energy near the (3,3) resonance where $\sigma(\pi^+p)$ and $\sigma(\pi^-n)$ is favored over $\sigma(\pi^+n)$ and $\sigma(\pi^-p)$ by 9:1. Despite this strong asymmetry in the interaction between incident pion and valence nucleon, one would not expect a large π^+/π^- asymmetry in scattering from a self

conjugate nucleus such as ^{16}O since protons and neutrons should participate equally in transitions to pure isospin states.

These states in ^{16}O , which are believed to be of a $(p_{3/2}^{-1}, d_{5/2})$ configuration, have been seen previously in one-nucleon transfer reactions and in inelastic proton scattering at medium energies.²⁶ 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, the $T_<$ state becomes mostly a proton state (π^+ enhanced) and the $T_>$ state is predominantly a neutron state (π^- enhanced). In the case of ^{16}O three 4^- states occur 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 $T=0$ state mixes with the $T=1$ state, resulting in the $T=0$ state becoming predominantly a proton state and the $T=1$ state becoming predominantly a neutron state. However, when the $T=1$ state mixes with the upper $T=0$ state, the energy denominator of the mixing changes sign, which results in the $T=0$ state above becoming primarily neutron in composition while the $T=1$ state gains in proton strength from this second mixing. This cancellation due to mixing with both upper and lower $T=0$, 4^- states result in a nearly isospin pure $T=1$ middle state as it retains nearly equal

proton and neutron transition amplitudes, which is indicated by the symmetric excitation of this state with π^+ and π^- . The net result is that the lower T=0 state becomes mostly a proton state and the upper T=0 level becomes mostly a neutron state.

For three 4^- states to appear so close in energy, it is reasonable to conclude that they are substantially configuration mixed as well. Preliminary analysis of the isospin mixing, including the configuration mixing, indicates that both the lp-lh off-diagonal charge dependent mixing matrix elements are about 210 keV, when constrained to the same value, and are 188 ± 29 and 140 ± 21 keV when allowed to vary independently in a slightly different formulation of the problem. The configuration mixing parameters obtained from fits to the data are in rough agreement with the wavefunctions of Millener and Kurath.²⁷

iii. Summary

Charge dependent mixing of nuclear states has been studied in a comparison between π^+ and π^- inelastic scattering. In ^{12}C , the known 1^+ T=0 and T=1 doublets have shown mixing consistent with previous measurements, and two new strongly mixed isospin doublets {with $J^\pi = 2^-$ & 4^- } have been discovered. In ^{16}O ,

three-state mixing for the known $J^\pi = 4^-$ states has been successful. Five charge dependent matrix elements exceeding 100 keV have been extracted from these pion data. Four of these matrix elements are new measurements of large H_{10} , whereas one, H_{10} for $^{12}\text{C}(1^+)$, is in agreement with previous work. Taken with previously measured large values for H_{10} using doublets in $^8\text{Be}(2^+)$, $^{12}\text{C}(1^+)$, and $^{16}\text{O}(2^-)$, results in a total of seven experimentally determined charge-dependent matrix elements exceeding 100 keV. As a group, these are consistently larger than expected from early calculations using residual Coulomb interactions alone. Recent calculations, spurred by previous measurements of three large values for H_{10} , have resulted in correspondingly larger calculated values for H_{10} without employing any short-range charge dependence in the nuclear force. However, all these data and calculations have been confined to a narrow mass range ($A=8-16$). At present, the sign of each of the seven (measured) H_{10} matrix elements is consistent with a $\sum_p e^2/r_{ij}$ mixing interaction, using a single configuration particle-hole description of each nuclear state. If short-range charge dependence plays a significant role in the nucleus, a sign reversal might occur in H_{10} from that expected using the residual Coulomb interaction, when future (π^\pm, π^\pm) data is taken over an increased mass range. The present π^+ versus π^- inelastic scattering method for extracting $\{H_{10}\}$ in a test of short-range

charge dependence is especially promising for two reasons: (1) In this preliminary effort using only two targets, ^{12}C and ^{16}O , the number of measured H_{10} matrix elements exceeding 100 keV has more than doubled, {increased from 3 to 7}, and (2) the available mass range for measuring both the size and sign of H_{10} is significantly increased as the π^+ versus π^- inelastic scattering comparison method may be used in a systematic study of all the other self-conjugate nuclei.

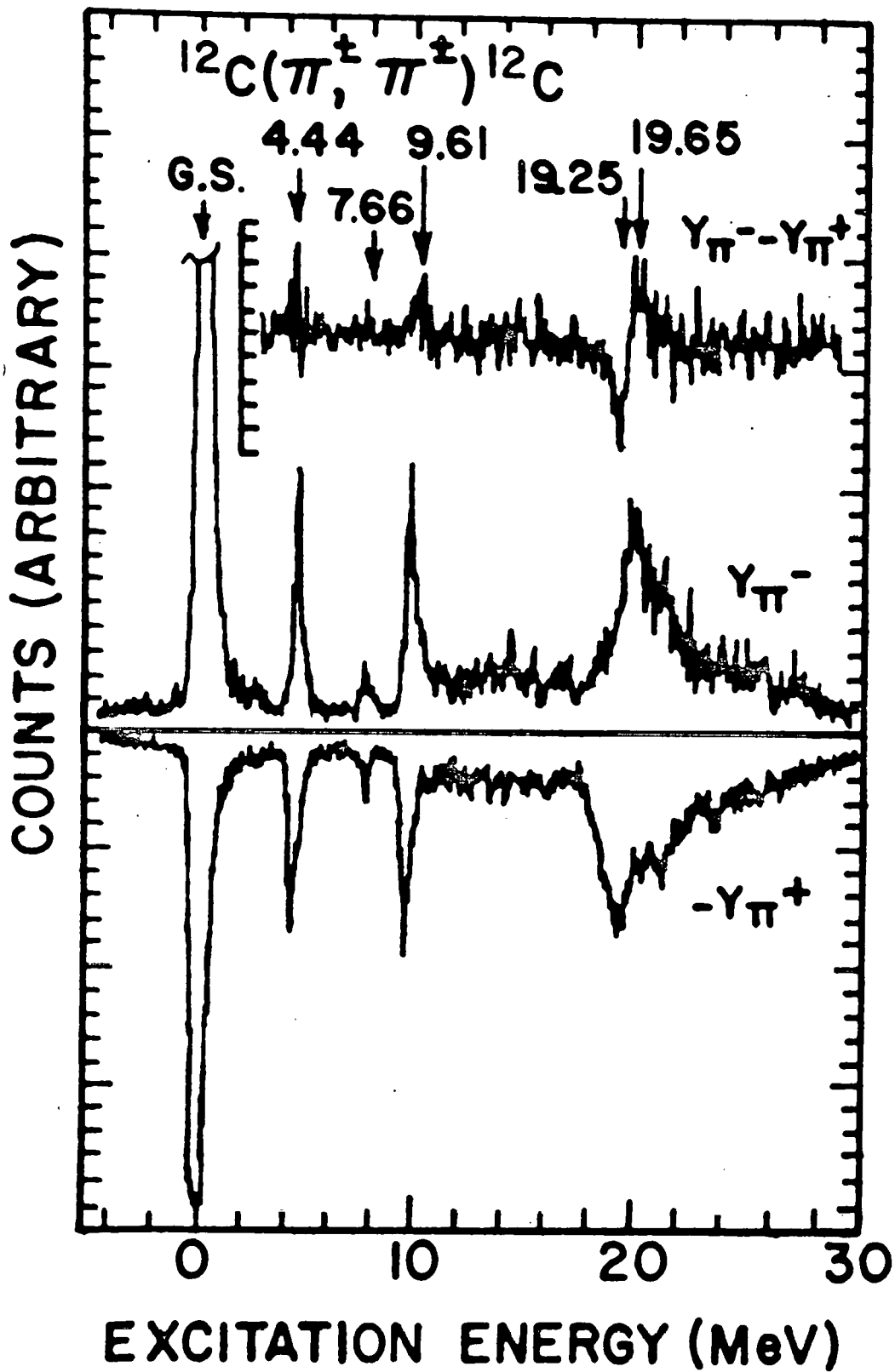


Figure 6. π^- inelastic scattering from ^{12}C near 70° at 162 MeV. The inset shows the subtracted yield, $Y_{\pi^-} - Y_{\pi^+}$.

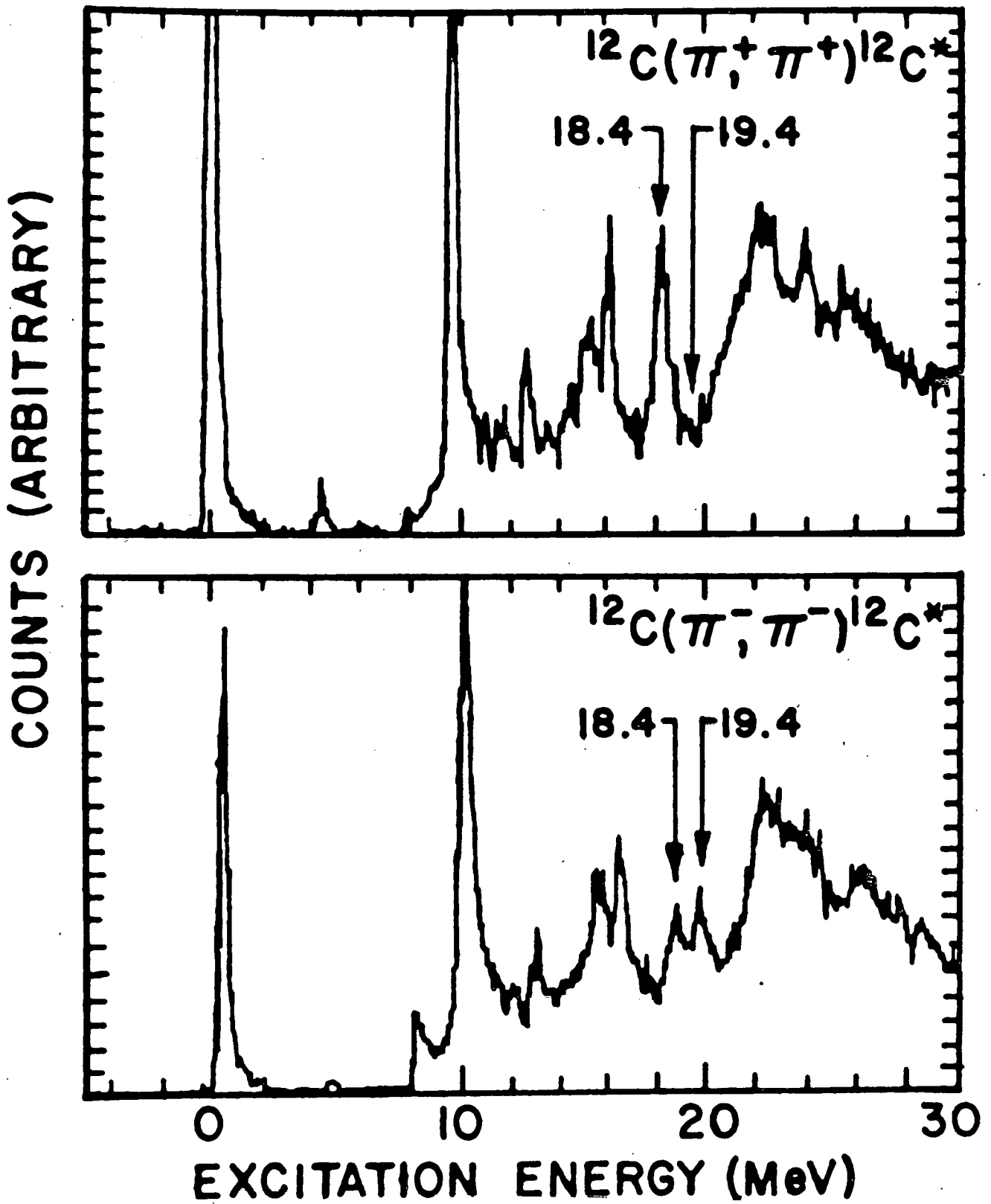


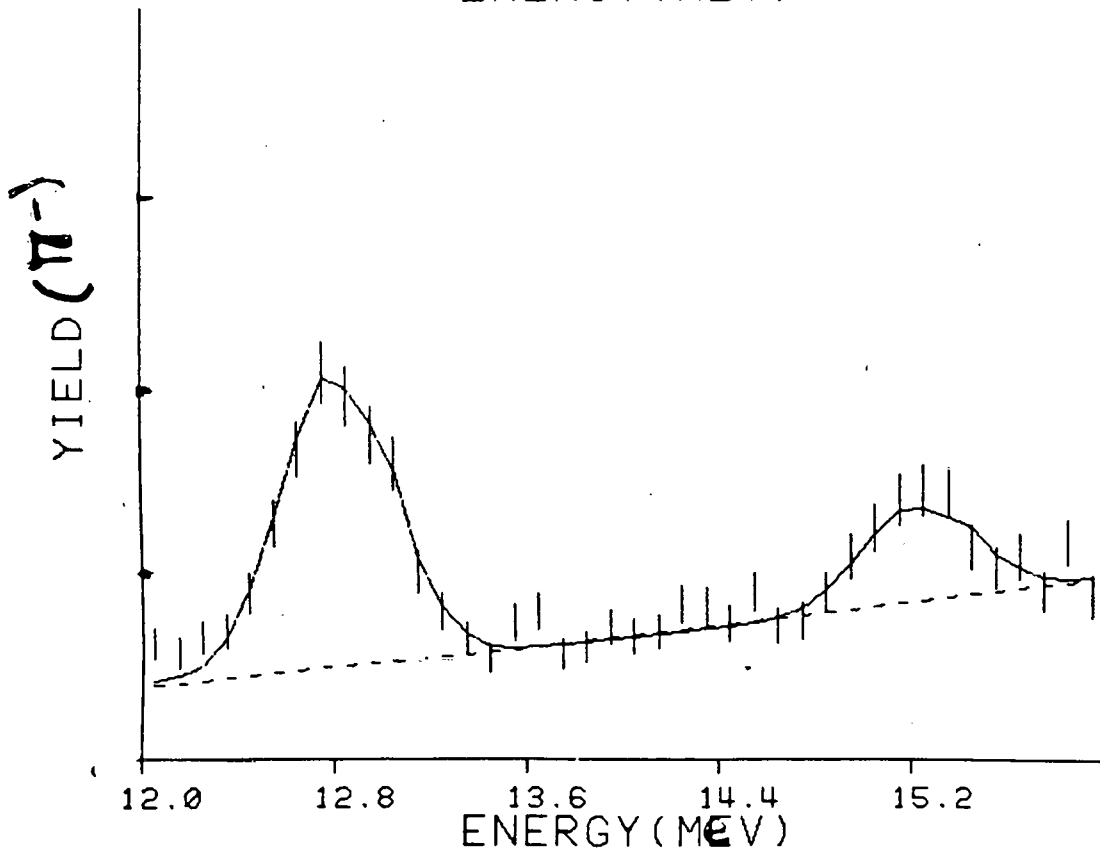
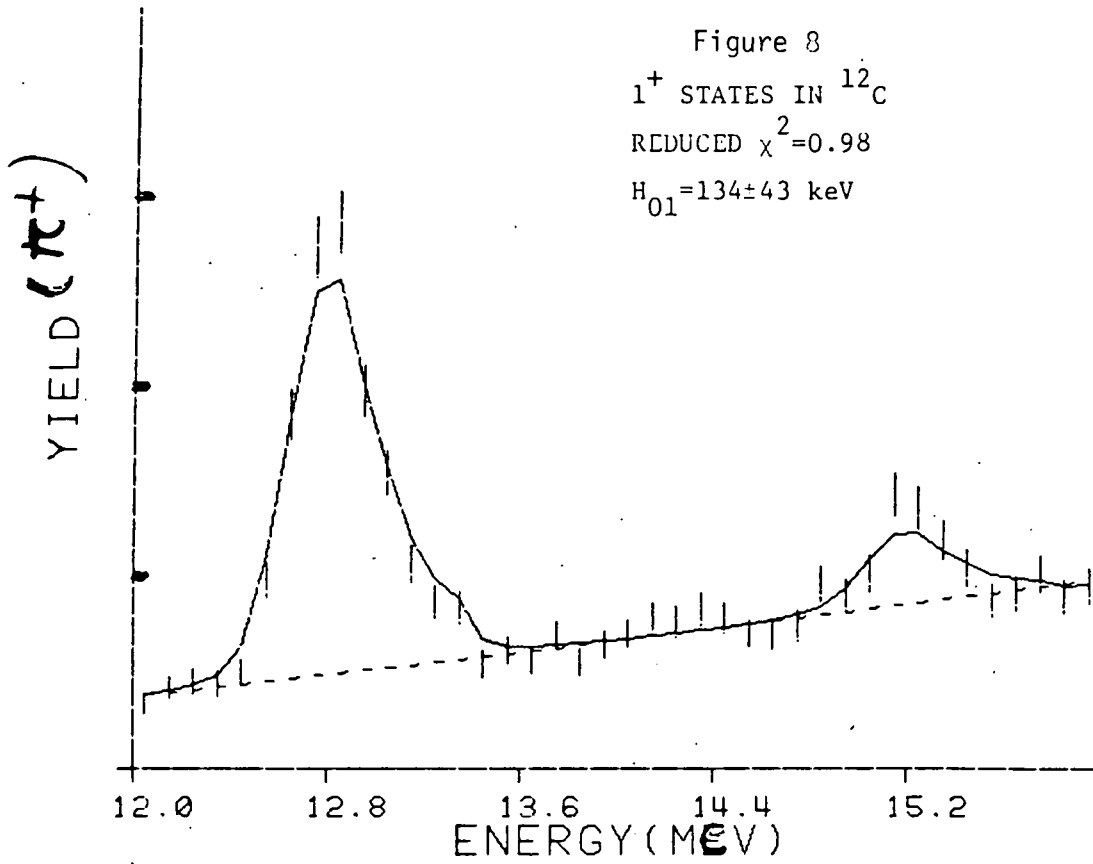
Figure 7. π^+ inelastic scattering spectra from ^{12}C at 25° and 180 MeV.

Figure 8

1^+ STATES IN ^{12}C

REDUCED $\chi^2=0.98$

$H_{01}=134\pm 43$ keV



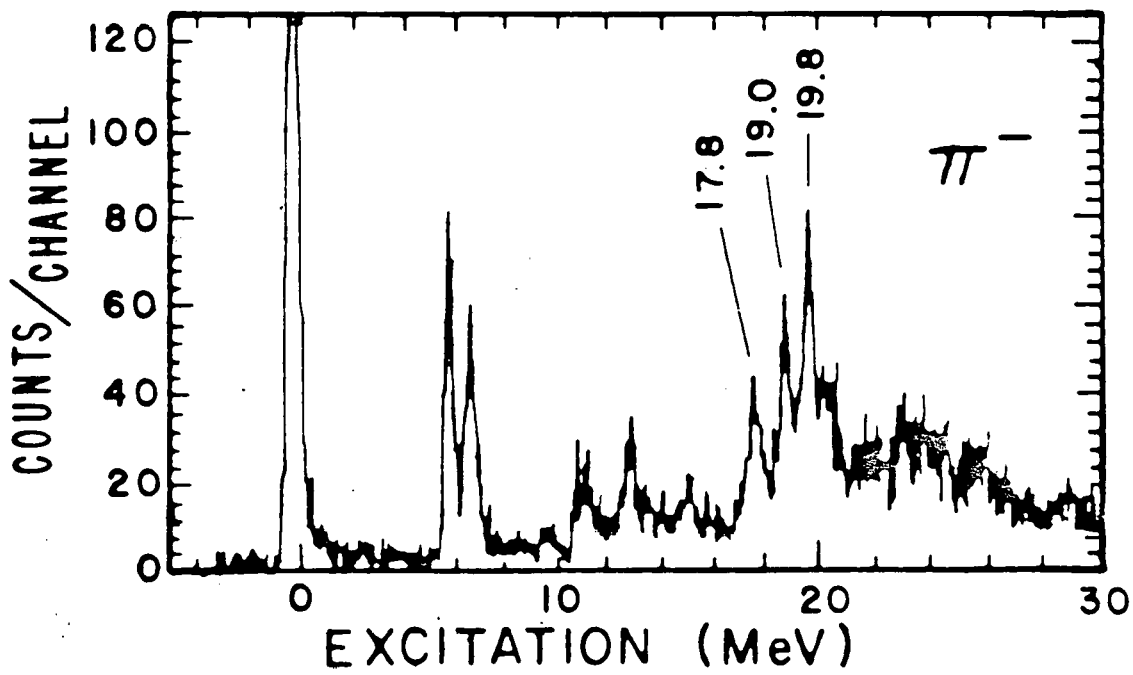
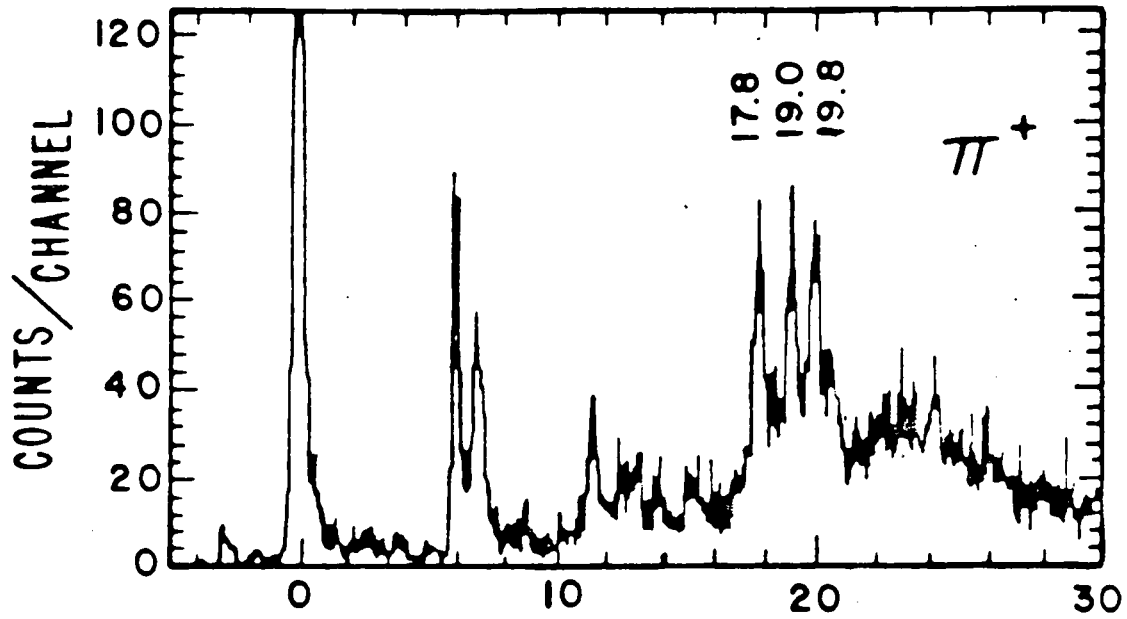


Figure 9. π^\pm inelastic scattering on ^{16}O near 70° at 164 MeV.

C. The Pion Inelastic Scattering Reaction Mechanism (Texas,
LASL)

We felt it important to examine the reaction mechanism of pion inelastic scattering due to its importance in interpreting our results in Carbon, Oxygen, Calcium, Iron, and Lead. Several sets of data have been studied, each of which suggests a simple one-step interaction between the incident pion and the valence nucleon in inelastic scattering.

Inelastic scattering of π^+ from ^{12}C across the (3,3) resonance indicates large differences in the excitation function for states up to 25 MeV in excitation. The gross features of the observed energy dependence may be understood by remembering that at least a vector operator is required to excite unnatural parity states, whereas, the excitation of normal parity states may proceed through a scalar as well as a vector operator. In a one-step process the vector operator²⁸ is the $\sigma \cdot L$ part of the pion-nucleon interaction. This operator leads to a $\sin\theta$ dependence of the π -nucleus amplitude, which at fixed momentum transfer will decrease with incident energy. In contrast, normal parity states exhibit increasing strength with increasing incident energy due to a $\cos\theta$ dependence, assuming the scalar operator dominates. The first 2^+ , 0^+ and 3^- normal parity states

and the 2^- and 4^- non-normal parity states show reasonable agreement (Figure 10).

The agreement of the data with such a simple picture suggests the appropriateness of a single-body operator representation for the pion-nucleon interaction. As a further test that the reaction-mechanism is relatively straightforward, optical model calculations for ^{12}C over the energy range of 120 to 280 MeV have been performed. The calculations utilize only a Kisslinger potential, free pion-nucleon phase shifts, harmonic oscillator parameters from electron scattering and first order corrections for various nuclear effects and point interaction of the Kisslinger potential. The data and calculations are shown in Figure 11. The lack of agreement at back angles is presumably due to either the failure of the approximation used in the pion-nucleon to pion-nucleus center on mass angle transformation or the failure of the harmonic oscillator model to adequately describe the tails of the density distribution. However the agreement of the calculation to the data over the entire energy region is surprisingly good and much better than had been expected.

Figures 12 and 13 are angular distributions for π^+ scattering to the following excited states in ^{12}C : (2^+ , 4.44 MeV), (0^+ , 7.66 MeV), (3^- , 9.64 MeV), (2^- , 11.83 MeV), (1^+ , 12.71 MeV), (2^- , 13.35 MeV), (4^+ , 14.08 MeV), (1^+ , 15.11 MeV), (2^+ , 16.11 MeV), (2^- , 18.36 MeV), (4^- , 19.25 MeV), (3^- , 20.68 MeV), (2^+ , 21.50 MeV), and (1^- , 21.88 MeV). In each case, the angular distributions were taken at the following incident π^+ energies: 100, 116, 140, 160, 180, 200, 230, 260, and 291 MeV. These inelastic angular distributions show the consistent feature of the first angular minimum decreasing in angle as the incident energy is increased, consistent with single-step direct-inelastic-excitation of these excited states.

Siciliano has calculated angular distributions (Figures 14, 15, and 16) for four pion inelastic transitions in ^{12}C $\{(0^+, \text{g.s.}) \rightarrow (2^+, T=0,1) \text{ and } (0^+, \text{g.s.}) \rightarrow (1^+, T=0,1)\}$ at three different incident energies: 116, 180, and 260 MeV. These Distorted Wave Impulse Approximation (DWIA) calculations employ microscopic one-body density-matrix elements (obdme's) in a clear separation of the nuclear structure from the reaction mechanism.²⁹ The calculated angular distributions reproduce quite well both the shapes and the magnitudes of these four inelastic transitions at all three energies, especially considering these are parameter-free calculations. The success of these comparisons of

data with DWIA calculations provides further evidence for a simple, one-step reaction mechanism for pion inelastic scattering, not only on the (3,3) resonance, but above and below as well.

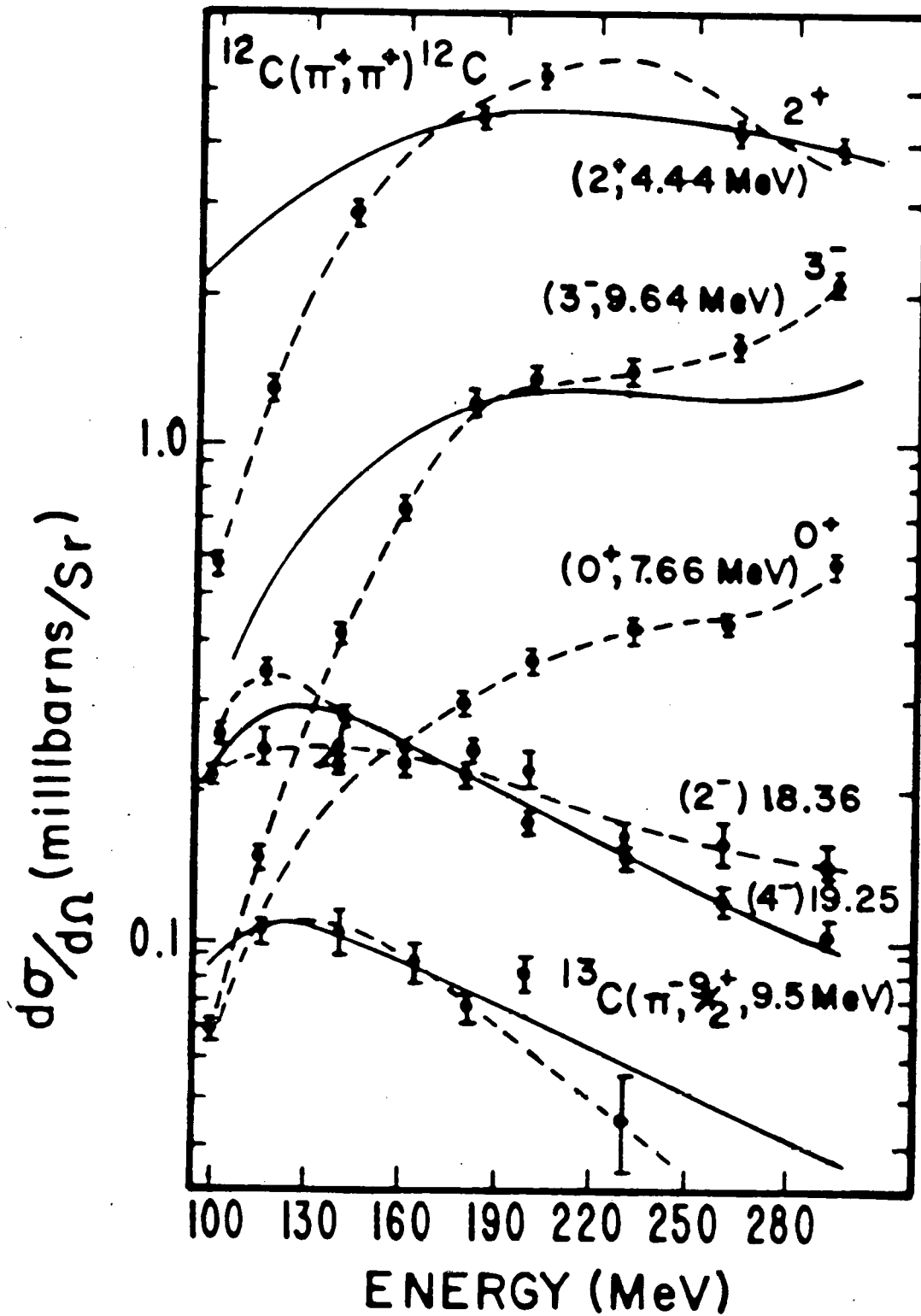


Figure 10. Excitation functions at fixed momentum transfer for π^\pm on ^{12}C and on ^{13}C . The momentum transfer was chosen to maximize the yield for each state.

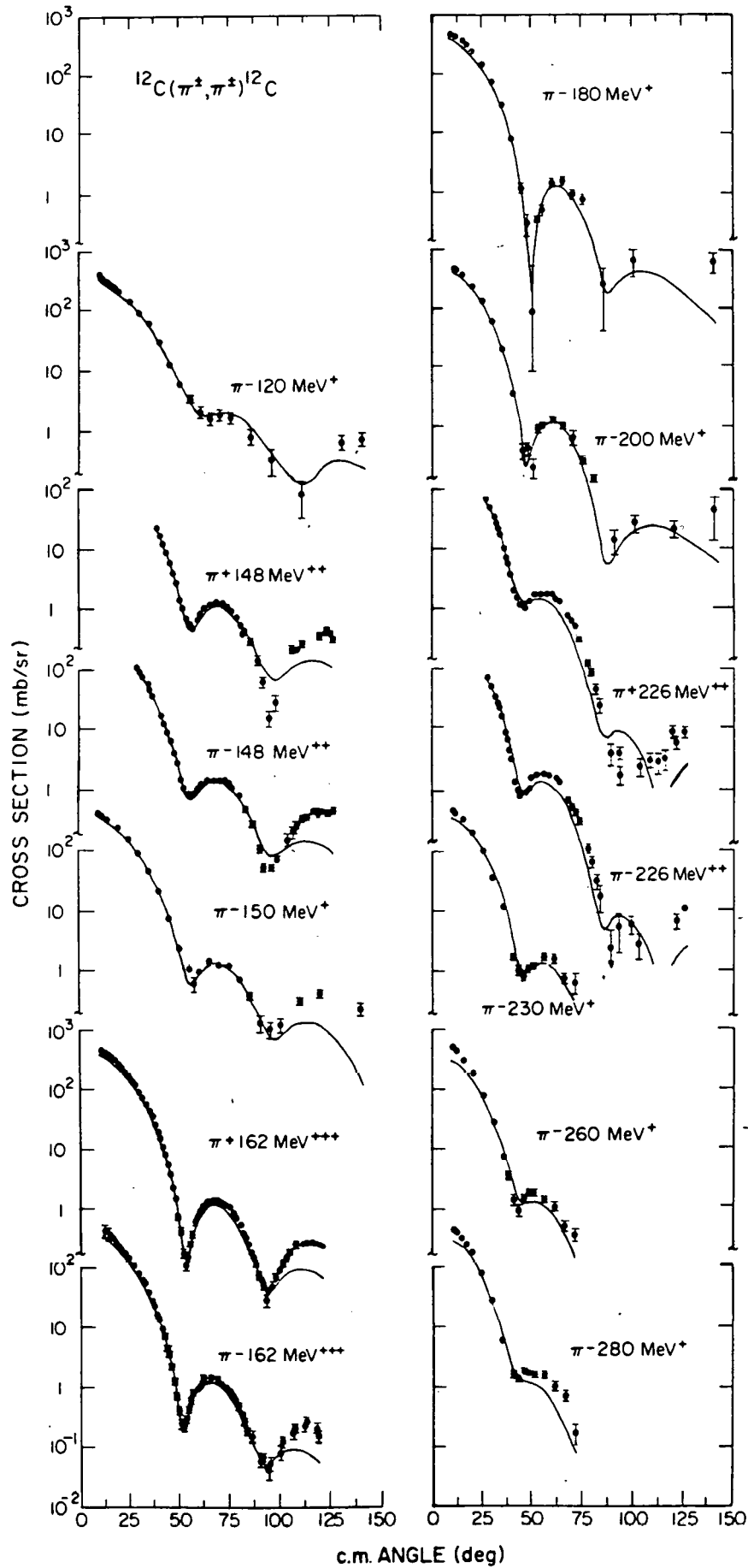


Figure 11. Optical model calculations for ^{12}C .

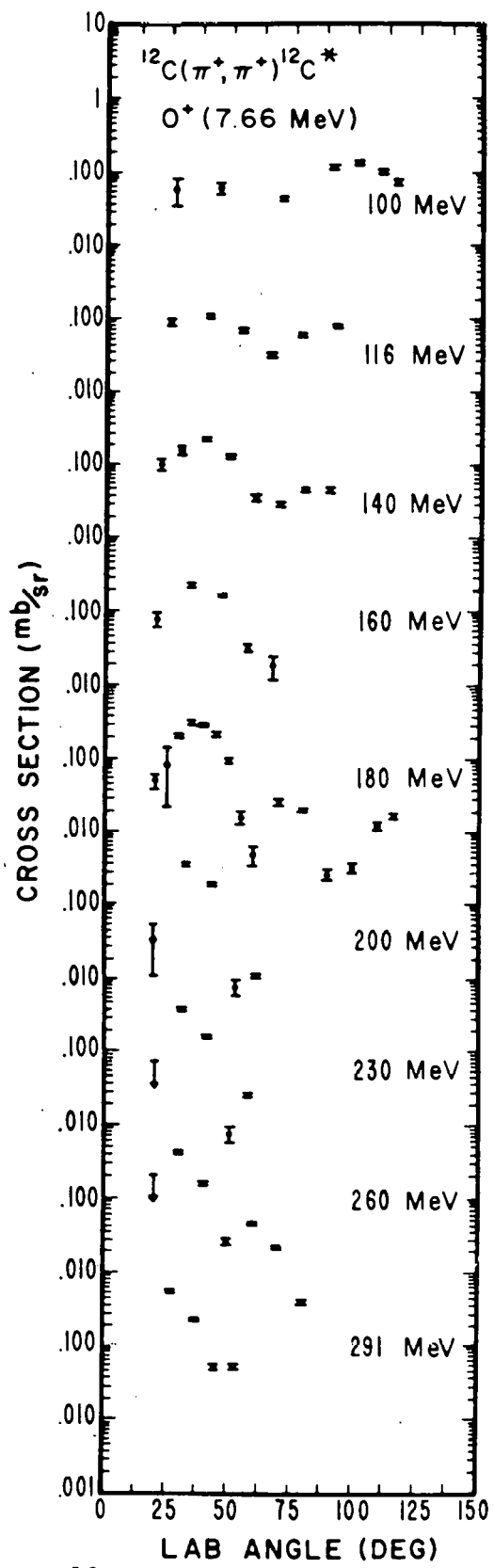
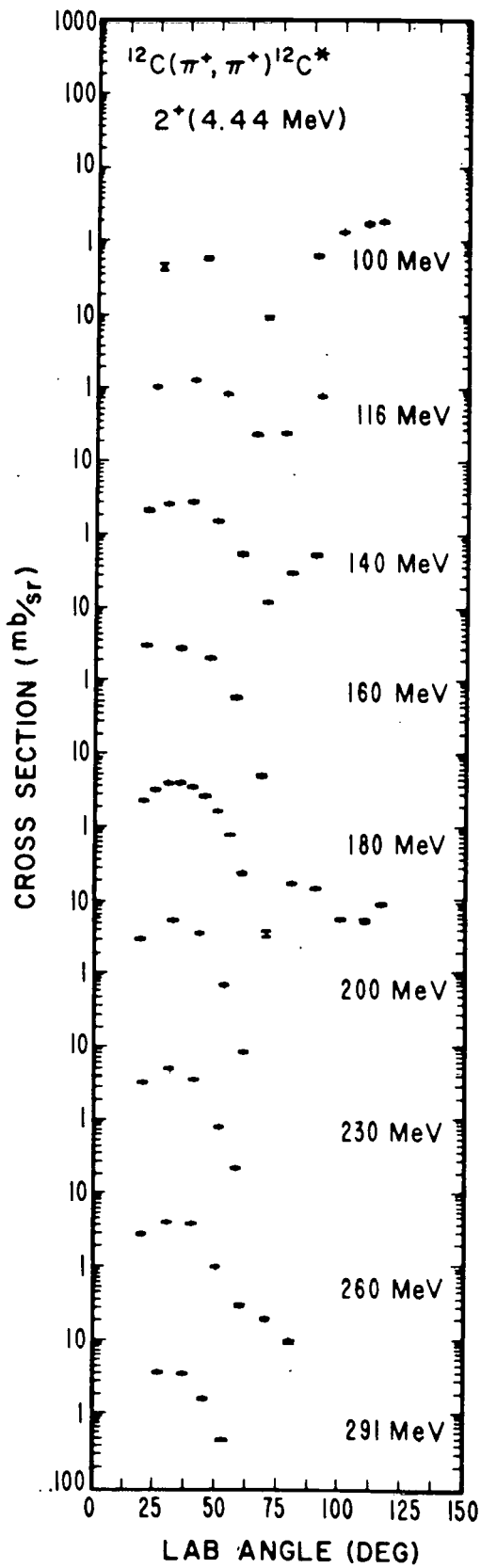


Figure 12A. Angular distributions for ^{12}C for π^+ scattering to 0^+ and 2^+ excited states.

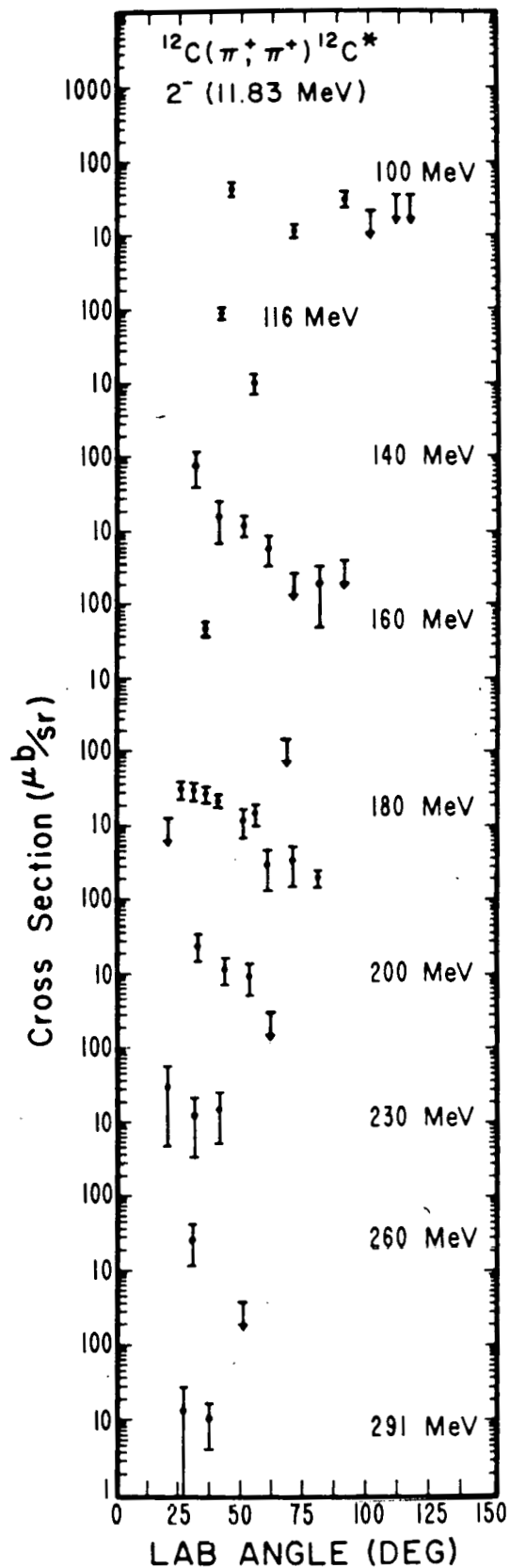
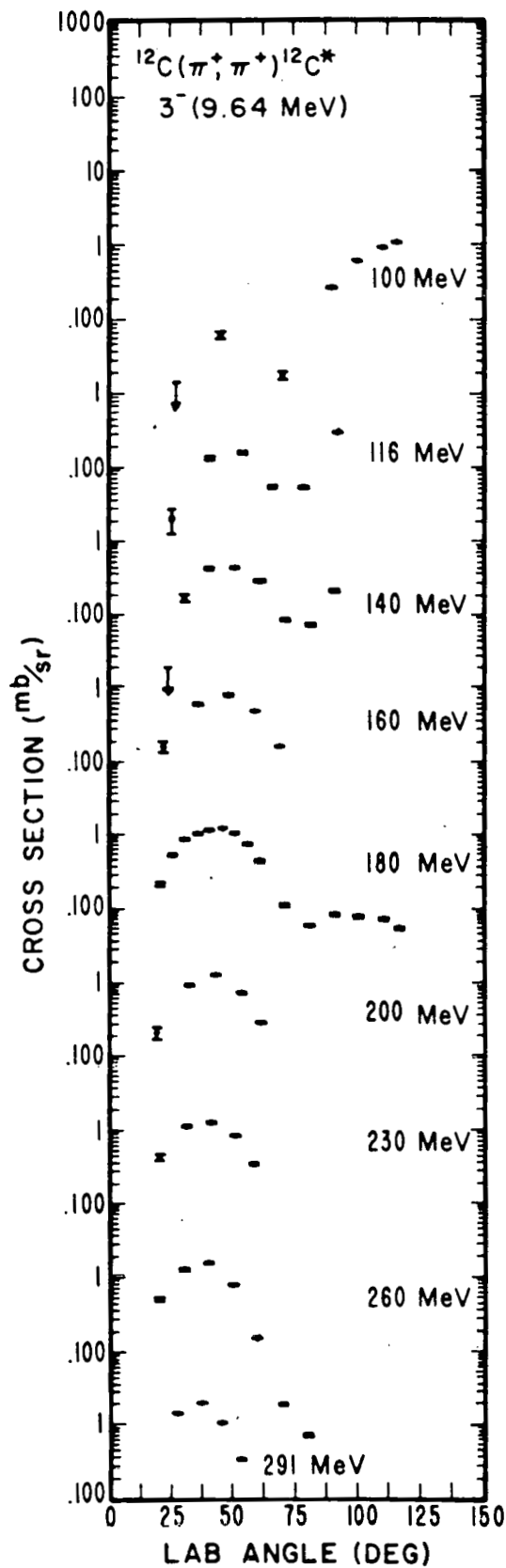


Figure 12B. Angular distributions for ^{12}C for π^+ scattering to 3^- and 2^- excited states.

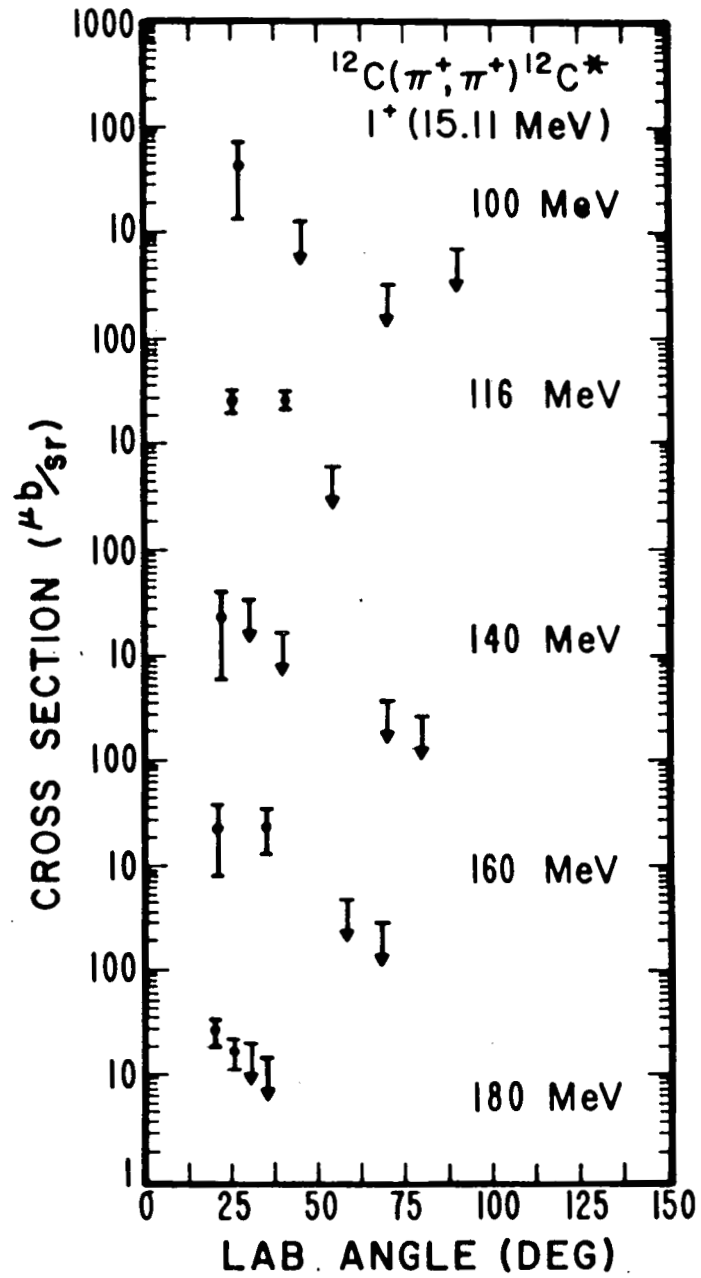
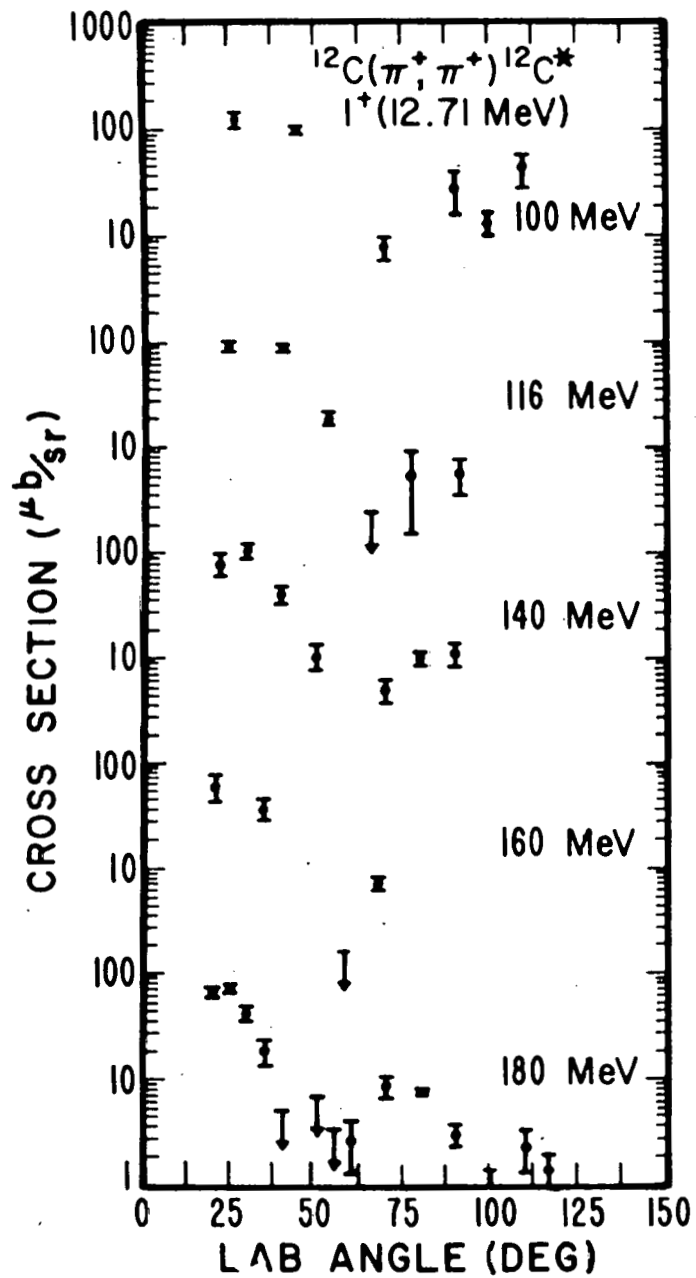


Figure 12C. Angular distributions for ^{12}C for π^+ scattering to 1^+ excited states.

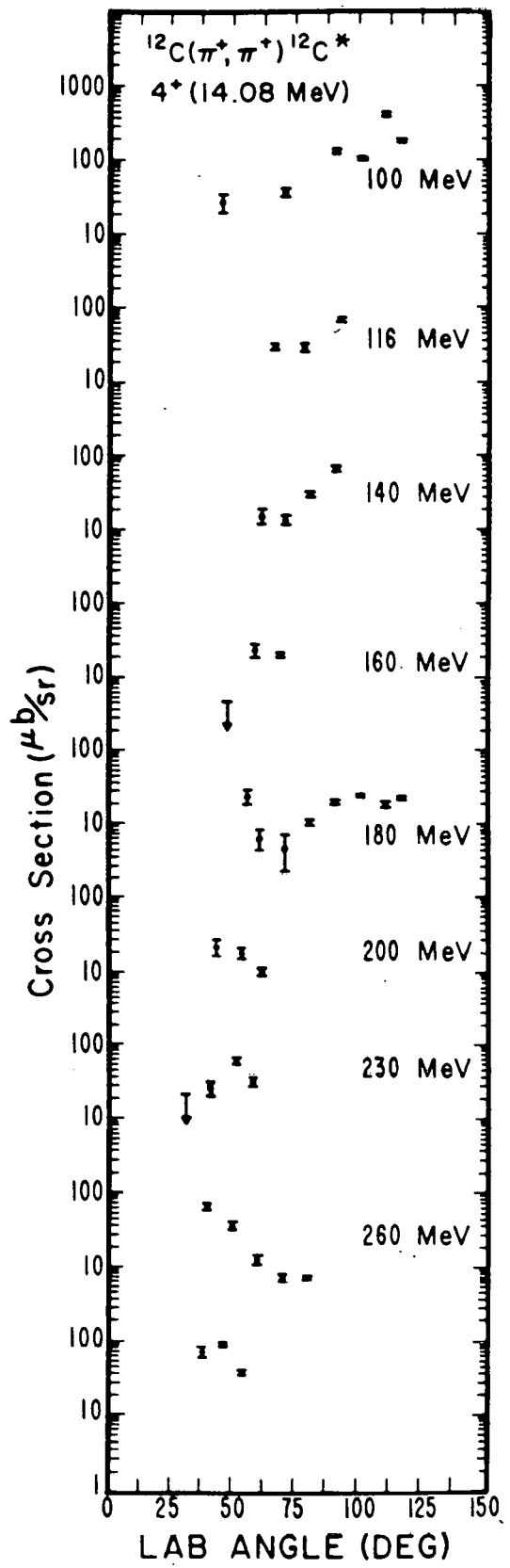
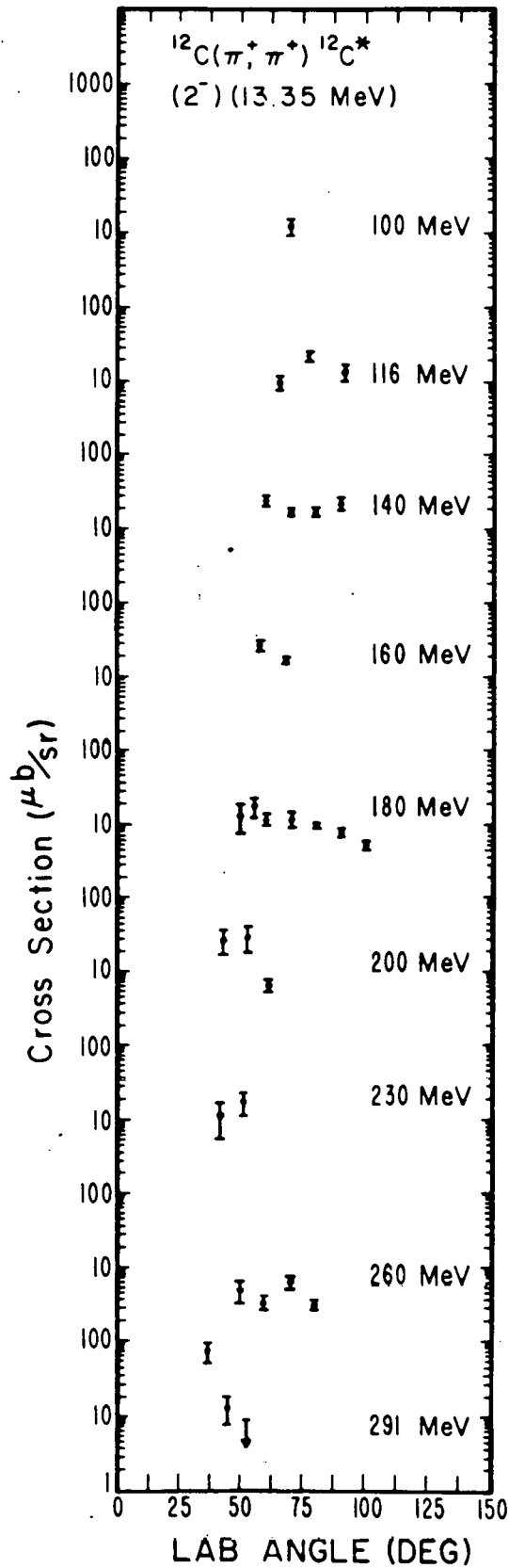


Figure 13A. Angular distributions for ^{12}C for π^+ scattering to 2^- and 4^+ excited states.

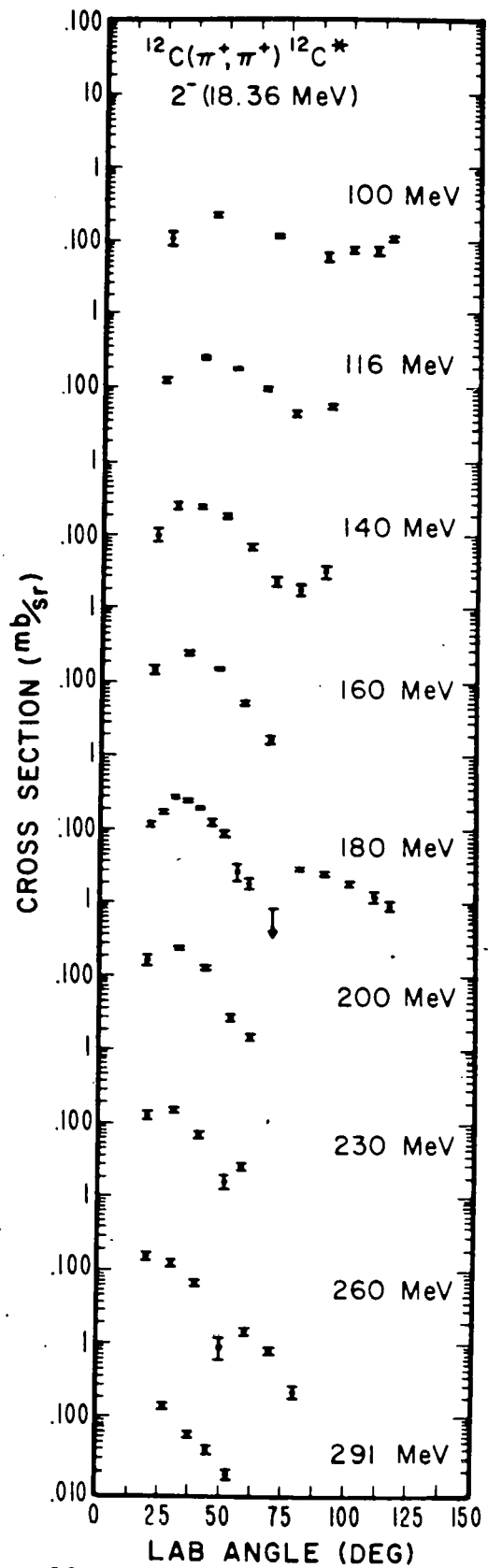
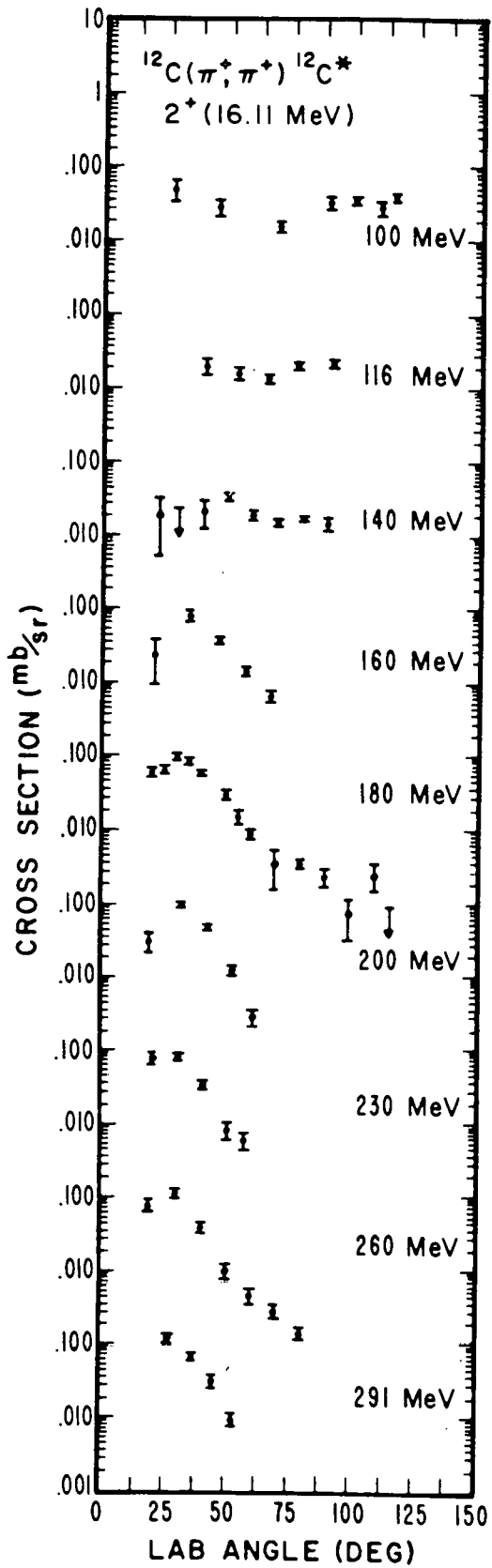


Figure 13B. Angular distributions for ^{12}C for π^+ scattering to 2^+ and 2^- excited states.

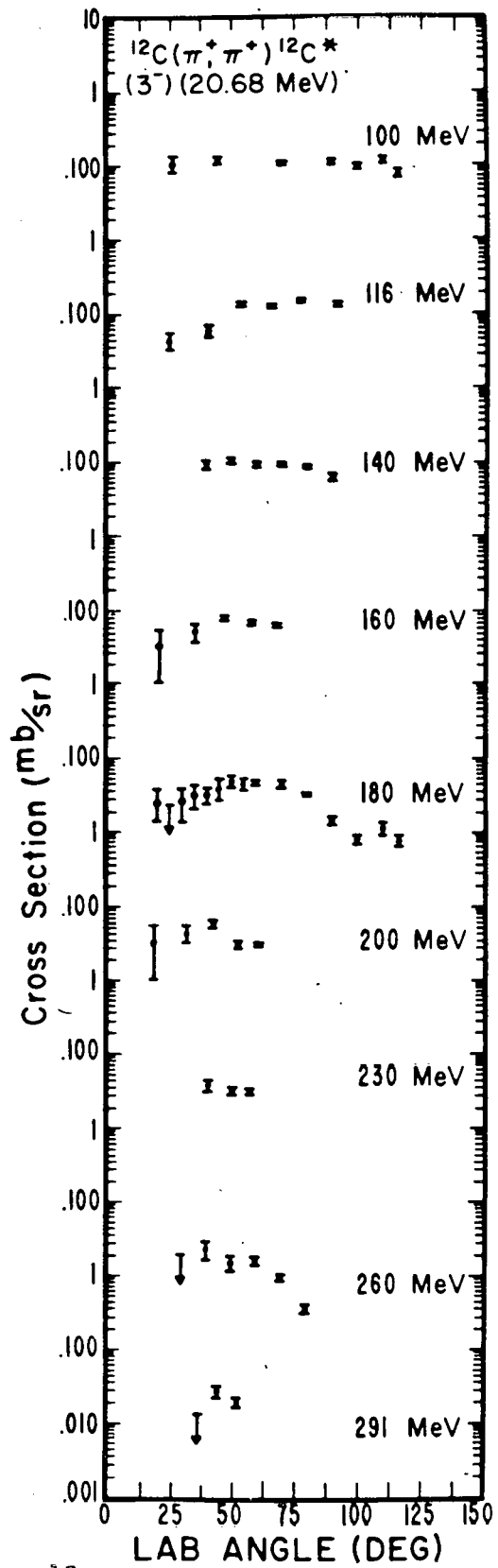
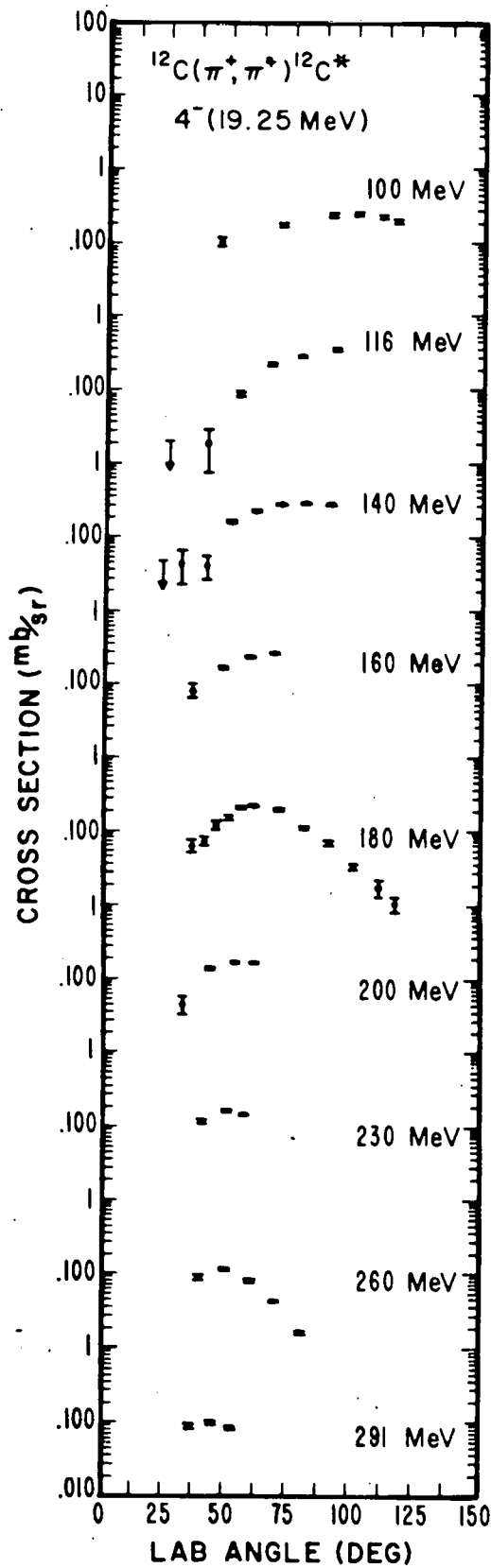


Figure 13C. Angular distributions for ^{12}C for π^+ scattering to 4^- and 3^- excited states.

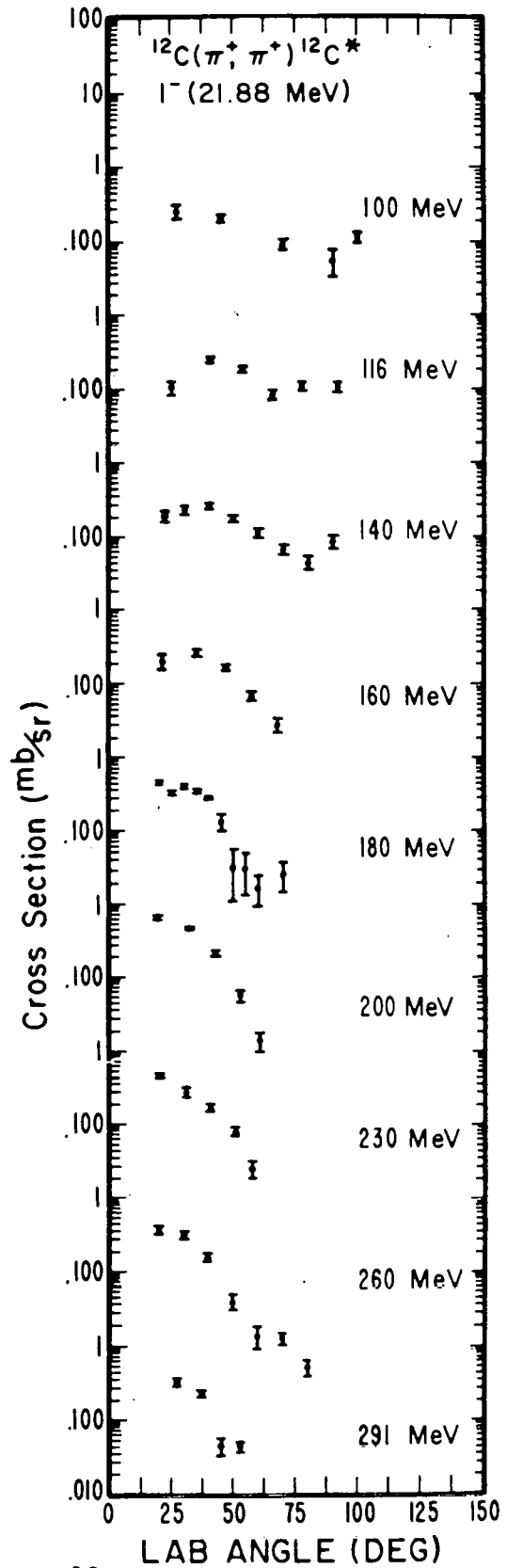
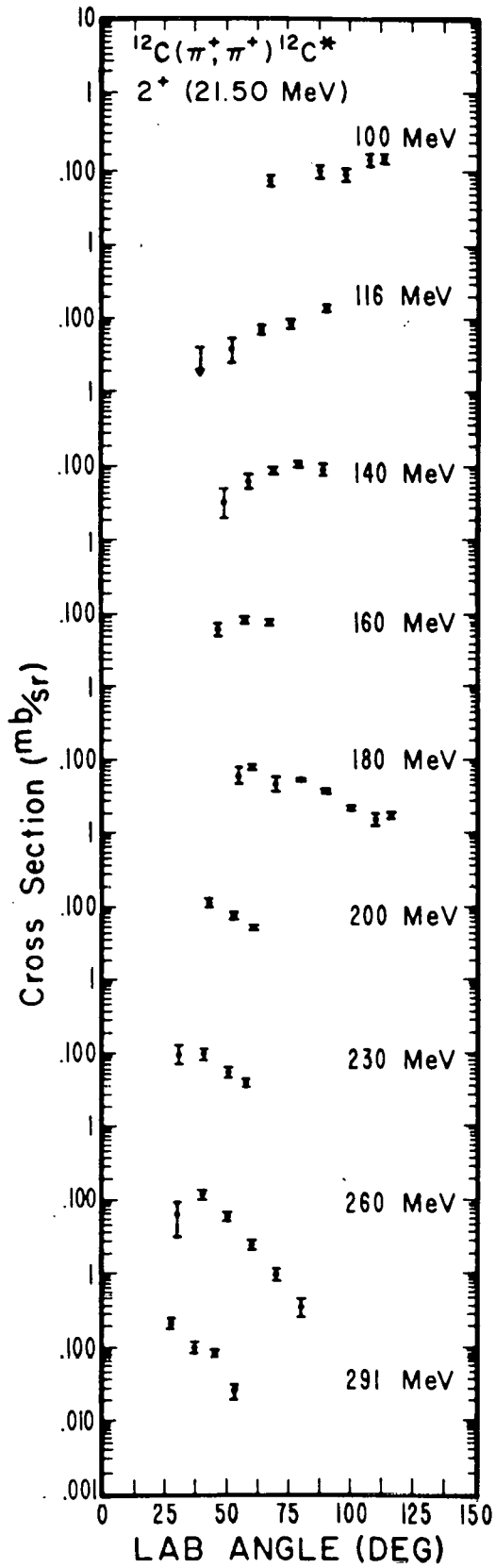


Figure 13D. Angular distributions for ^{12}C for π^+ scattering to 2^+ and 1^- excited states.

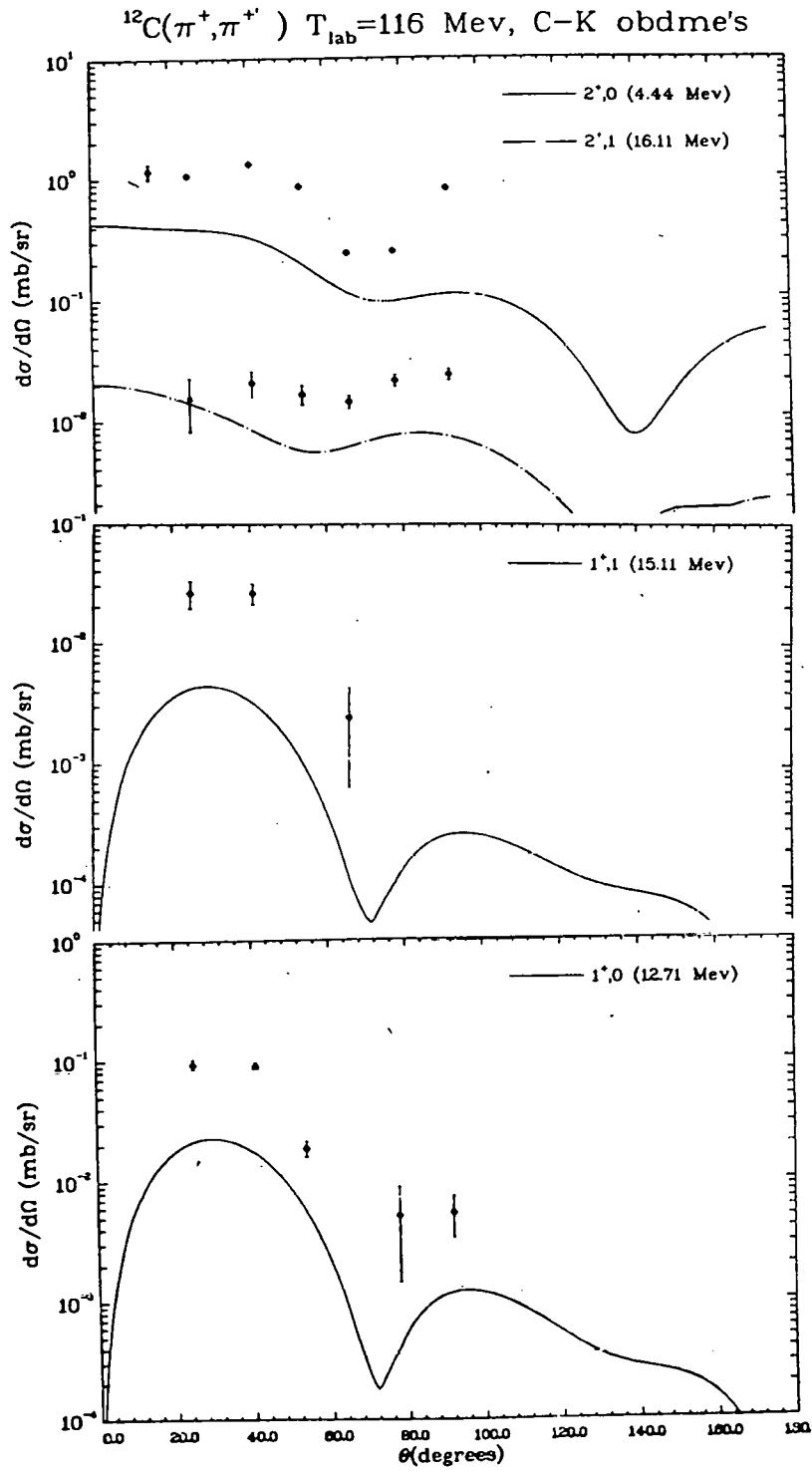


Figure 14. Distorted Wave Impulse Approximation calculations.

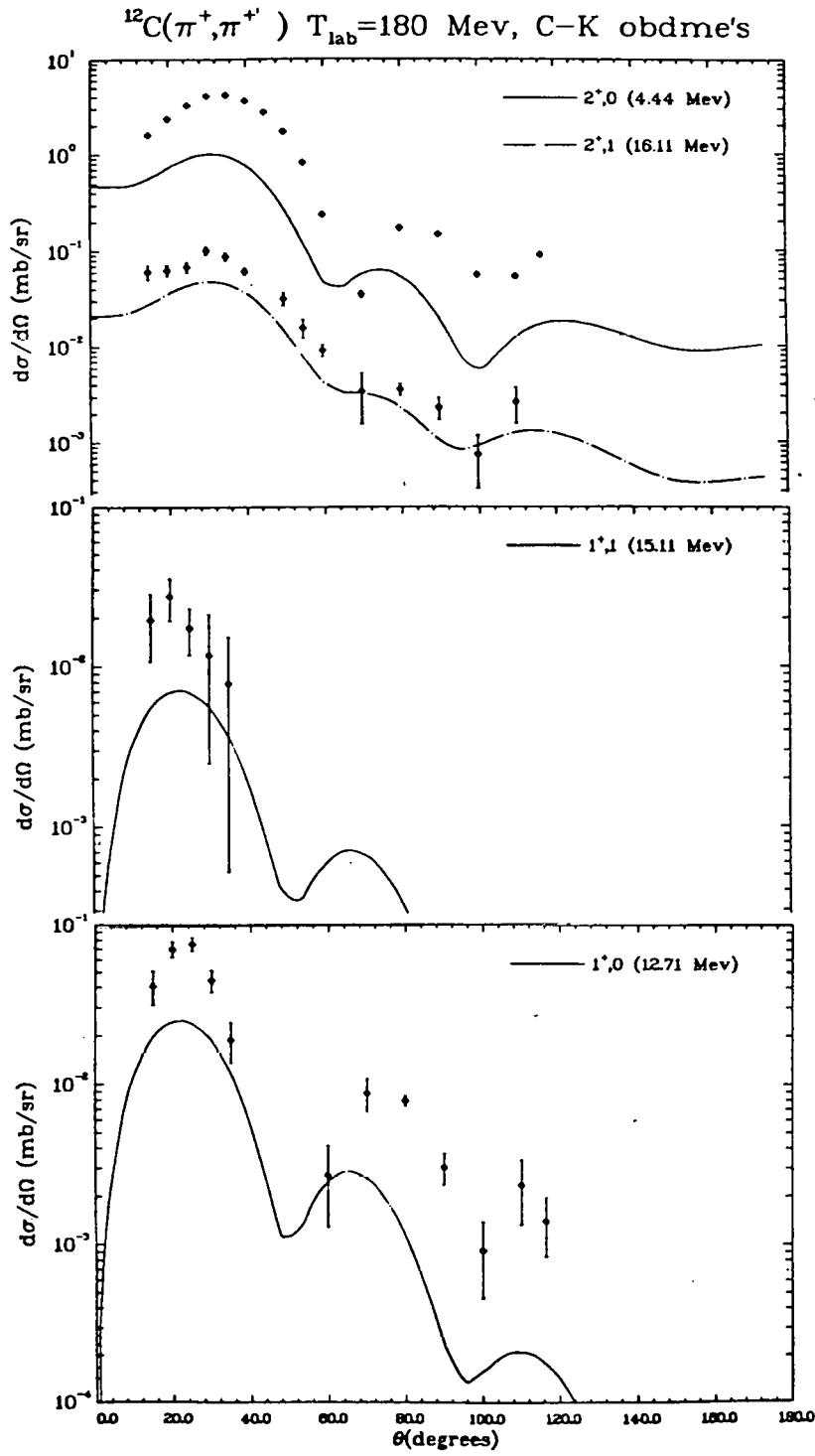


Figure 15. Distorted Wave Impulse Approximation calculations.

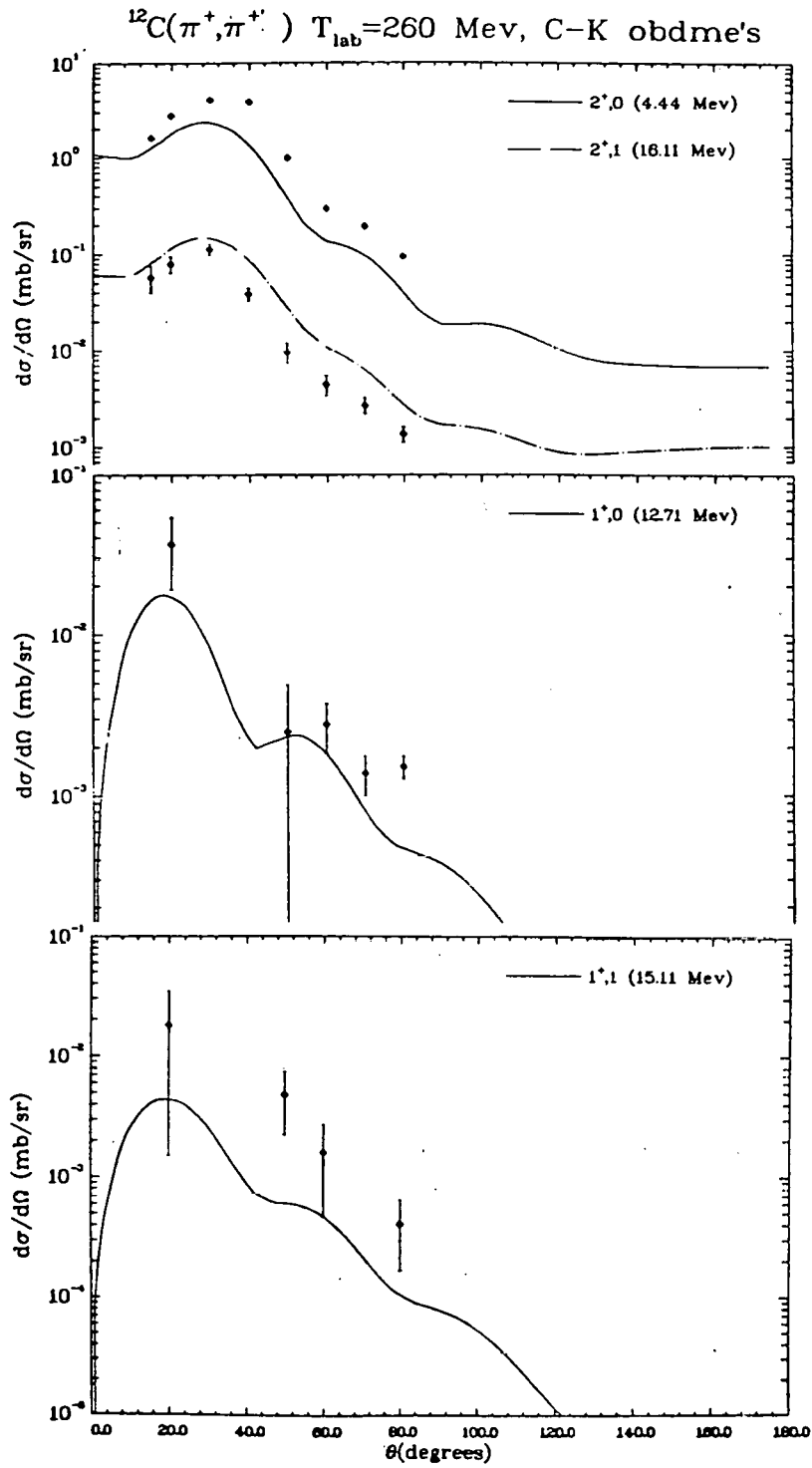


Figure 16. Distorted Wave Impulse Approximation calculations.

D. Quasielastic Pion Scattering (Texas, Virginia, New Mexico State, LASL)

A principal medium-energy scattering mechanism is the quasielastic process in which a nucleon is knocked out of a nucleus without the remaining nucleons actively participating in the process. In the past, quasielastic scattering has been rigorously but exclusively investigated with protons and electrons. The quasielastic reaction involving pions is thought to proceed in the same manner. For pion energies near the (3,3) resonance, multiple scattering and distortion effects due to the strong meson-nucleon interaction are expected to influence pions more strongly than the distortion effects with protons, since the calculated mean free path of pions through nuclear matter in this energy region is shorter. Multiple scattering effects have already been noticed in the data taken by Ingram, et al.³⁰

We are reporting the results of a one-arm measurement of the differential cross section, $d^2\sigma/d\Omega dE$, for π^\pm scattering from ^{12}C and $^{40,44,48}\text{Ca}$ in the quasielastic region using a magnetic spectrometer, the EPICS facility, to detect the pions. Data was taken at 180 MeV (60°) and 291 MeV (60° and 120°). Elastic data on Hydrogen was taken at each spectrometer setting to measure the absolute cross section as well as the background. The

calibration measurements were made with CH_2 and graphite so that the ^{12}C background could be directly subtracted to yield the Hydrogen peak and its associated background, a background due principally to muons produced by pions decaying in the spectrometer dipoles. Published cross sections for pion-proton scattering were used to normalize the data (Rowe, et al.³¹).

The resulting cross sections with errors are plotted in Figures 17, 18, and 19. The curves traced in the figures are predictions based on a Fermi gas model. To first order, quasielastic scattering can be described by pions scattering from a collection of protons and neutrons having a Fermi momentum distribution, resulting in pion-nucleon cross sections approaching their free values (free cross section model). A more involved calculation using the Fermi gas approximation employed in electron quasielastic scattering^{32,33} was done for pion scattering using Monte Carlo methods. Z protons and N neutrons were assumed to be uniformly distributed throughout a sphere of radius $r_0 A^{1/3}$ and to have a Fermi momentum distribution with the maximum Fermi momentum value taken from the fits to electron scattering data.³³ The direction of motion of the nucleons was taken to be isotropic. The interaction probabilities and angular distributions used were the free total and differential pion-nucleon cross sections. Binding effects and pion charge

exchange were included in the calculation but Coulomb effects were neglected. Neutrons and protons were treated separately. The program recorded the energy distribution of pions emerging within specified angles and generated the corresponding cross sections per nucleon for both single and multiple scattering.

The fraction of pions undergoing many successive scatterings was found to be fairly large (about 50%). Events having as high as a ten-fold scattering before emerging were not uncommon. Multiple scattering cross sections are the solid curves drawn in the figures. Dashed lines represent single scattering predictions (^{12}C only). A multiple scattering description does not coincide exactly with the details of the experimental curves, but it does substantially better than its single scattering counterpart. Part of the data unmatched by the multiple scattering curve (the small-energy-loss portion on the 60° distribution) we believe includes inelastic scattering leading to nuclear excitations; i.e. the residual nucleus plays an active role in the interaction. For the π^-/π^+ ratios, both the Monte Carlo calculations and the free cross section model follow the experimental trend. A few startling facts emerge from the experiment. In the π^- results, the ^{44}Ca cross sections at 60° are greater than the ^{48}Ca cross sections, and the ^{44}Ca and ^{48}Ca cross sections at 120° (291 MeV) are nearly equal, in direct

opposition to previous theoretical models. The π^- cross sections are predicted to increase with neutron number and π^+ cross sections should likewise prefer protons (as seen in free π -nucleon scattering). For the π^+ results, ^{48}Ca cross sections are smaller than ^{44}Ca cross sections, as expected, but the ^{44}Ca cross sections are larger than those for ^{40}Ca .

The Monte Carlo multiple scattering method reproduces other features of the data with some success, such as the increased cross section at 120° , in comparison with the 60° values — a point at which the free cross section model and single scattering utterly fail. Multiple scattering, being angle independent, appears to be essential in describing the lack of angular coherence in the 291 MeV distribution. An accurate separation of the experimental data into multiple and single scattering contributions is unfeasible due to the almost complete overlap and the uncertainties inherent in the calculations. The data, however, do verify the large nuclear cross section at a pion energy of 180 MeV, an energy computed to be a minimum of the pion mean free path in nuclear matter.

In conclusion, many qualitative features of the data are reasonably well reproduced by a model of incoherent multiple scattering by pions from a Fermi gas of nucleons with a uniform,

spherical distribution and the use of free pion-nucleon scattering probabilities. Successes of the multiple scattering picture are: reproducing general experimental trends, correctly predicting π^+/π^- ratios and the comparative magnitudes of ^{44}Ca and ^{48}Ca cross sections to those of ^{40}Ca , and the dominance of 120° scattering over 60° scattering at 291 MeV. Single scattering and free cross section descriptions are considerably less successful. Multiple scattering remains the most important ingredient of pion scattering in the quasielastic region.

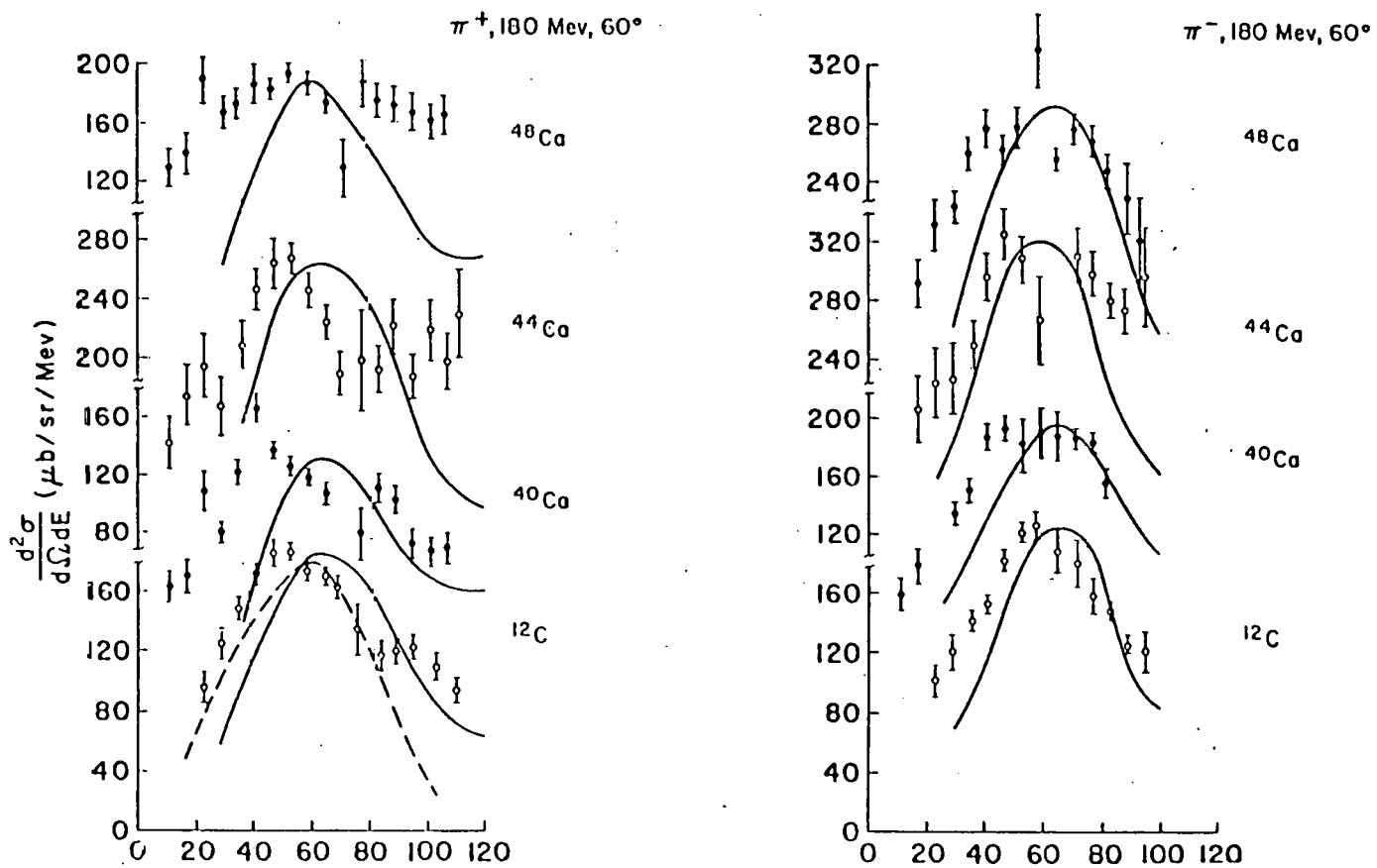


Figure 17. π^\pm scattering from calcium isotopes and carbon. Solid curves are multiple scattering cross sections based on a Fermi gas model. Dashed lines are single scattering calculations.

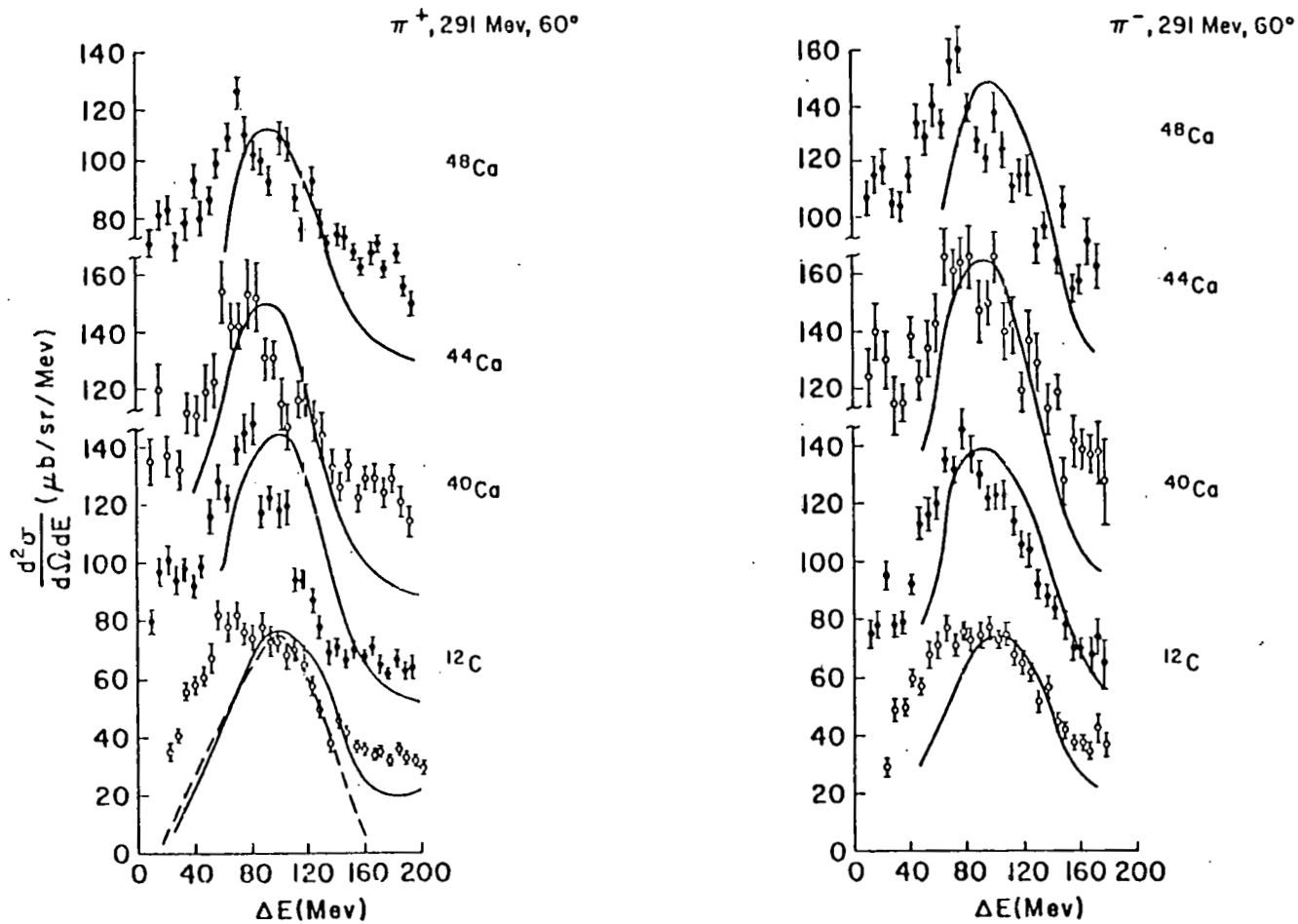


Figure 18. π^\pm scattering from calcium isotopes and carbon. Solid curves are multiple scattering cross sections based on a Fermi gas model. Dashed lines are single scattering calculations.

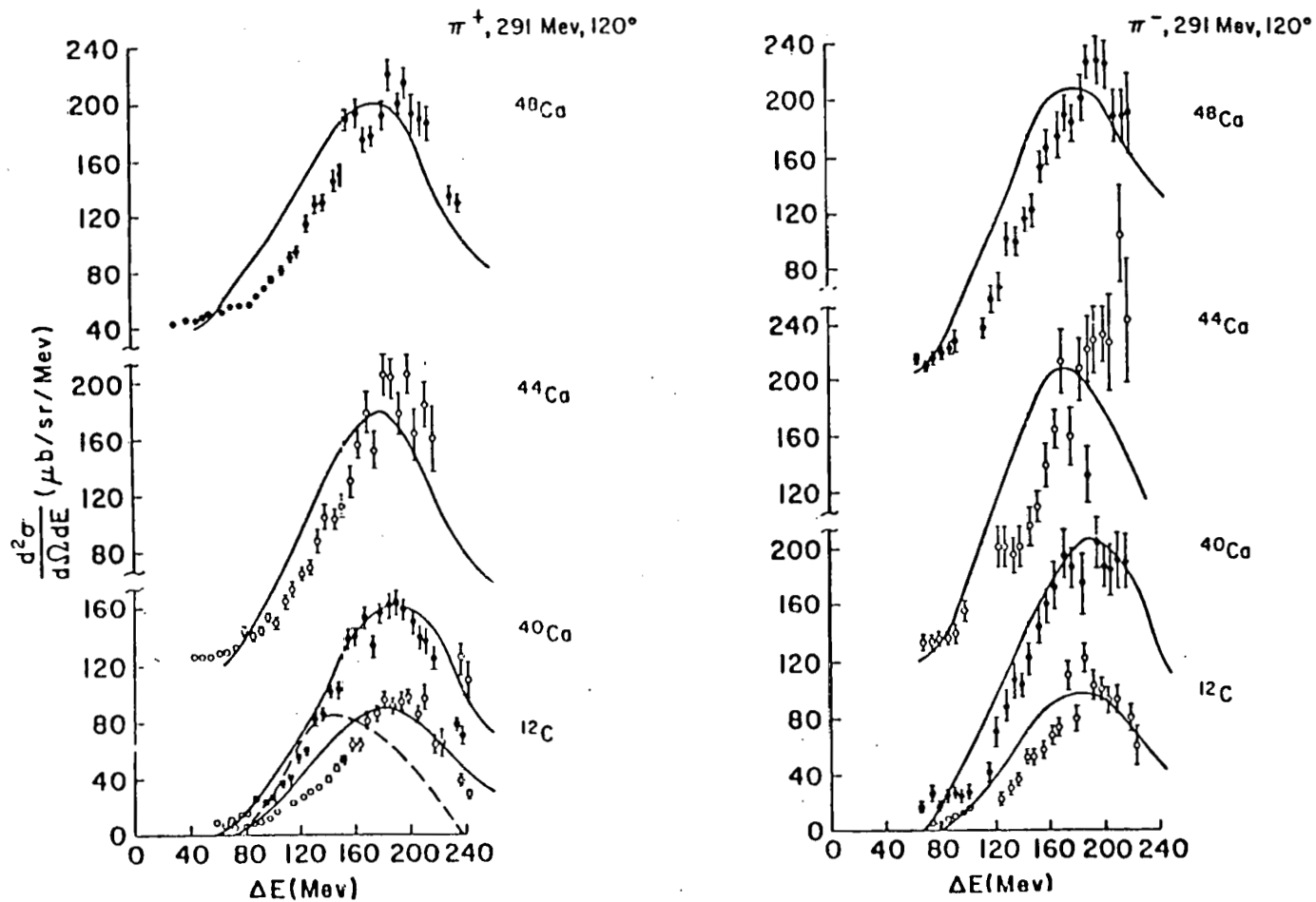


Figure 19. π^\pm scattering from calcium isotopes and carbon. Solid curves are multiple scattering cross sections based on a Fermi gas model. Dashed lines are single scattering calculations.

E. Mass Measurements with Pion Double Charge Exchange (Texas, New Mexico State, LASL)

To first order, the masses of isobaric multiplets fit the Isobaric Multiplet Mass Equation (IMME):³⁴

$$M(A, T, T_z) = a(A, T) + b(A, T)T_z + c(A, T)T_z^2.$$

Deviations from this simple quadratic form are expected if the nuclear Hamiltonian includes three-body charge dependent forces or if sufficient isospin mixing occurs with a state of lower T . The quadratic form has been verified for isospin quartets, accurately assessing the masses of 21 out of 22 known quartets, the exception being $A=9$.³⁵

Since the pion double charge exchange reaction has significant cross section for transitions to non-analog states, (π^+, π^-) can be used to measure ground state masses in isospin quintets. Ground state masses of isospin quintets in the 1P and S-D shells, ^{12}O , ^{16}Ne , ^{24}Si , and ^{32}Ar were measured using targets of ^{12}C , ^{24}MgO , and ^{32}S .

Data were taken at a lab angle of 5° and an incident pion energy of 180 MeV. Ground states of ^9C and ^{13}O , whose masses are well-known,³⁶ were used to calibrate the missing mass spectra using targets of ^9Be and ^{13}C . The spectrometer resolution obtained with all targets was ~ 300 keV (intrinsic resolution, ~ 150 keV). The statistical errors for all mass measurements were less than 40 keV.

Experimental mass excesses and their errors along with known quintet members are given in Table I. Mass excesses for ^{12}O and ^{16}Ne represent improvements over previous values and the masses of ^{24}Si and ^{32}Ar are the first reported measurements for these isotopes. These values were fit with a least squares program to all orders in T_z . The resultant Chi-squared values for second order fits (Table II) are adequate without including higher order (dT_z^3 and $eT_z^4\dots$) terms.

The ground state masses for ^{12}O and ^{16}Ne plus the mass determinations of ^{24}Si and ^{32}Ar are consistent with the quadratic nature of the IMME. Two other quintets have been measured ($A=8,20$) with sufficient accuracy to test the IMME. For $A=8$, significant higher-order terms, $dT_z^3 + eT_z^4$, are required to fit the data. These terms probably arise from energy level shifts of two quintet members due to isospin-allowed particle-decay widths.

Measured values for the A=20 quintet which is bound to such decay show excellent agreement with the quadratic form of the IMME.

TABLE I . Properties of T=2 levels of isospin quintets in this study.

A	J ^π	T _z	Nucleus	E _x (KeV)	Mass Excess(KeV)	Ref.
12	0 ⁺	2	¹² Be	g.s.	25078(15)	11
		1	¹² B	12710(20)	26080(20)	12
		0	¹² C	27595.0(24)	27595.0(24)	13
		-1	¹² N	unknown	unknown	
		-2	¹² O	g.s.	32059(48)	this
16	0 ⁺	2	¹⁶ C	g.s.	13695(7)	10
		1	¹⁶ N	9928(7)	15610(7)	14
		0	¹⁶ O	22721(3)	17984(3)	14
		-1	¹⁶ F	unknown	unknown	
		-2	¹⁶ Ne	g.s.	24051(45)	this
24	0 ⁺	2	²⁴ Ne	g.s.	-5949(10)	10
		1	²⁴ Na	5969.0(16)	-2448.5(18)	15
		0	²⁴ Mg	15436.4(6)	1505.8(9)	15
		-1	²⁴ Al	5595(10)	5903(9)	16
		-2	²⁴ Si	g.s.	10682(52)	this
32	0 ⁺	2	³² Si	g.s.	-24092(7)	15
		1	³² P	5073.1(9)	-19231.6(12)	15
		0	³² S	12050(4)	-13965(5)	15
		-1	³² Cl	5033(10)	-8295.6(52)	17
		-2	³² Ar	g.s.	-2181(50)	this

TABLE II . Coefficients of the IMME and reduced χ^2 from least-squares fit.

A	a(MeV)	b(MeV)	c(MeV)	d(MeV)	e(MeV)	χ^2
12	27.5949(24)	-1.7478(118)	0.2441(62)			0.367
	27.5950(24)	-1.7628(273)	0.2434(63)	0.0044(72)		
16	17.9836(29)	-2.5949(89)	0.2233(57)			0.462
	17.9840(30)	-2.5995(112)	0.2220(60)	0.0025(37)		
24	1.5057(9)	-4.1757(36)	0.2222(31)			1.150
	1.5059(9)	-4.1767(37)	0.2194(38)	0.0028(21)		0.693
	1.5058(9)	-4.1818(75)	0.2235(66)	0.0060(47)	-0.0021(27)	
32	-13.9657(25)	-5.4686(25)	0.2027(23)			0.397
	-13.9663(37)	-5.4682(31)	0.2034(41)	-0.0005(22)		0.571
	-13.9651(40)	-5.4642(55)	0.1996(65)	-0.0033(43)	0.0019(25)	

F. Pion Inelastic Scattering on $^{40,42,44,48}\text{Ca}$ and ^{54}Fe

A comparison has been made of 180 MeV π^+ versus π^- inelastic excitation of low-lying collective states in the calcium isotopes, Z=20 series, $^{40,42,44,48}\text{Ca}$, and in the N=28 series, ^{48}Ca and ^{54}Fe . A preference is expected for valence protons to be excited in 3^- states and for valence neutrons to be excited in 2^+ states as the neutron $1f_{7/2}$ shell closure proceeds from ^{40}Ca to ^{48}Ca leading to the "Pauli blocking" of valence neutron transitions. The opposite preference is expected as the proton $1f_{7/2}$ shell closure proceeds from ^{48}Ca to ^{54}Fe leading to the "Pauli blocking" of valence proton transitions.

Ratios of $\sigma(\pi^-)/\sigma(\pi^+)$ for pion inelastic scattering to the three lowest 3^- states in ^{48}Ca at $\theta_{\text{lab}} = 33^\circ$ are 0.85, 0.90 and 1.4, respectively. Blocking due to the filled $1f_{7/2}$ neutron subshell is seen in the two lowest 3^- states. Simple sum-rule considerations predict a reversal of this effect for higher-lying states which is seen in the data for the third 3^- state. Both Blocking and Sum-rule effects may be seen in Figure 20, the π^- and π^+ spectra for inelastic scattering on ^{48}Ca are summed over several scattering angles.

Figure 21 and 22 are plots of the inelastic π^+ and π^- differential cross sections for the 2_1^+ and 3_1^- states in $^{42,44,48}\text{Ca}$, and ^{54}Fe , respectively. As can be seen, there is a marked preference of π^- over π^+ transitions for the 2_1^+ states in the $Z=20$ series; whereas, for the 3_1^- states, there is a discernable although not as marked preference of π^+ over π^- transitions. This difference can be interpreted qualitatively from the interaction between the shell and collective models of nuclear structure. Finally, for the 2_1^+ states in the $N=28$ series, the preference of π^- over π^+ transitions is substantial in ^{48}Ca while the preference is almost indistinguishable for the almost completely closed proton $1f_{7/2}$ shell in ^{54}Fe .

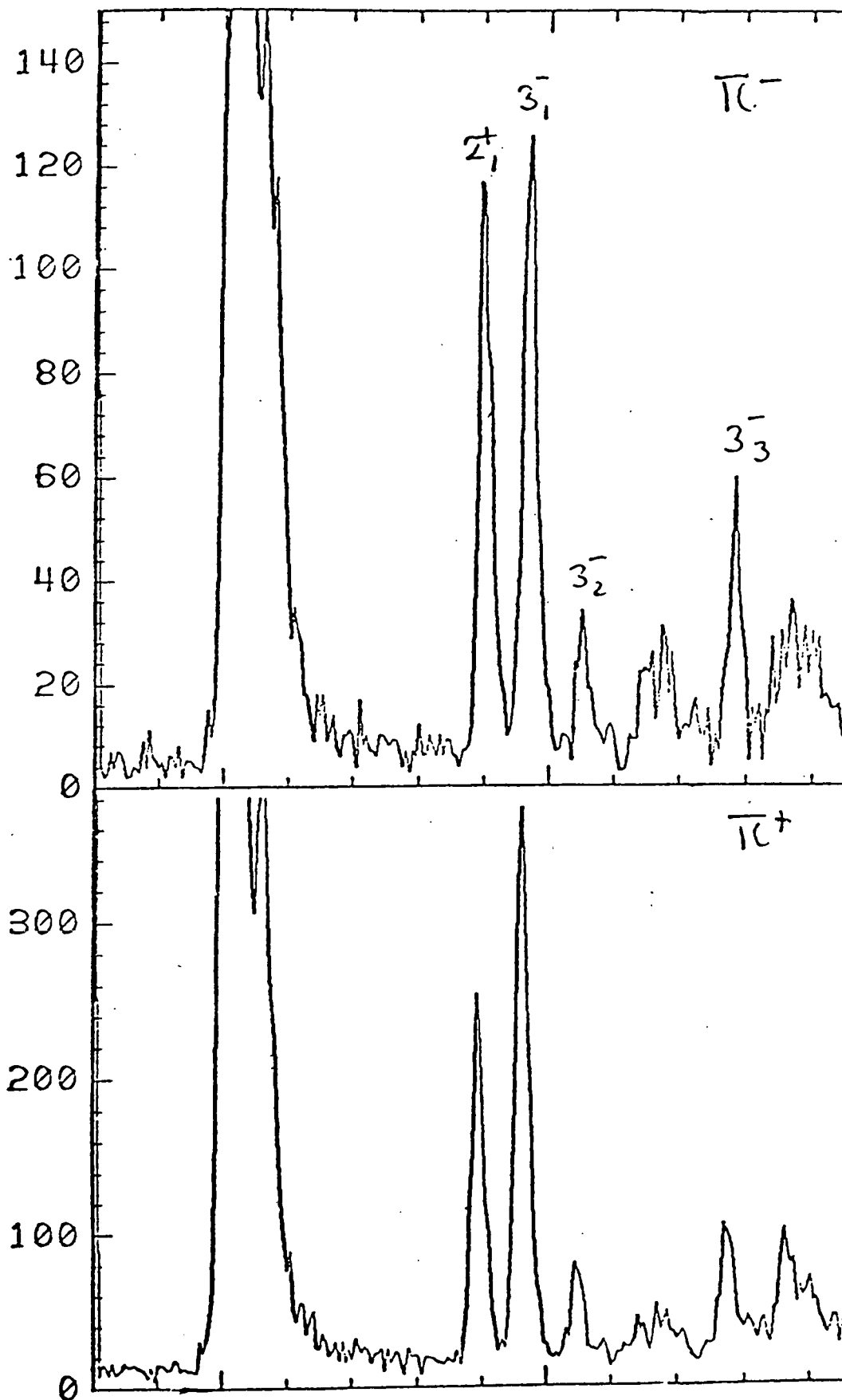


Figure 20. π^+ and π^- spectra for pion inelastic scattering to the three lowest states in ^{48}Ca

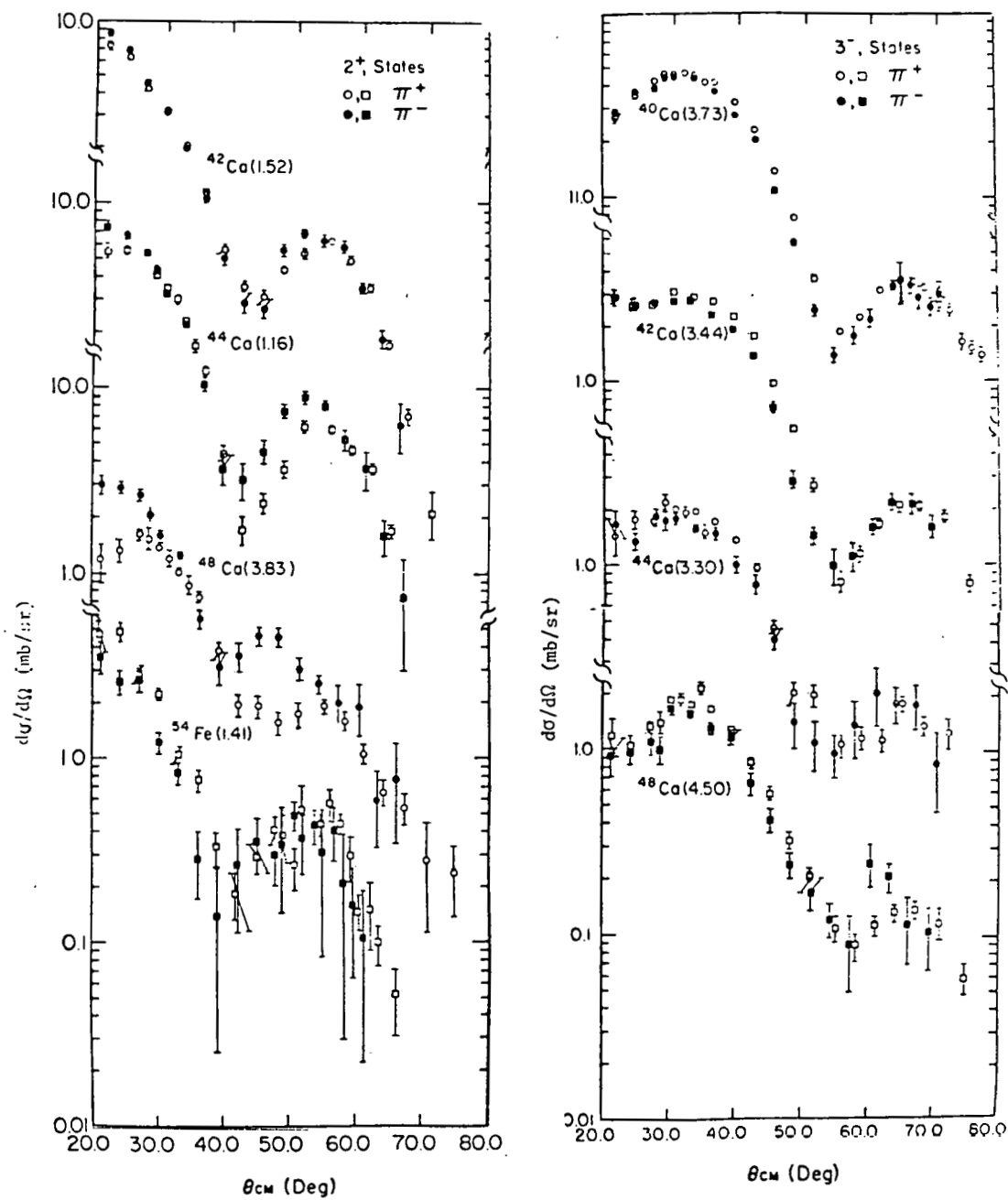


Figure 21 and 22. Inelastic π^+ and π^- differential cross sections for the 2_1^+ and 3_1^- states in $^{42,44,48}\text{Ca}$ and ^{54}Fe .

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III. RESEARCH WITH THE EXTERNAL PROTON-BEAM

A. Pion-Deuteron Production using 0.8 GeV Protons on Hydrogen

The virtual meson structure of the nucleon-nucleon field materializes into real, observable particles when sufficient energy is available. For almost 30 years, theory and experiment have been studying the meson production reaction: $pp \rightarrow d\pi^+$. This reaction not only furnishes insight into the fundamental nucleon-nucleon interaction, but also provides information concerning meson-nucleus interactions.

The range of the pion-nucleon interaction is thought to be less than the Compton wavelength of the meson involved. Assuming that the deBroglie wavelength of the pion is on the order of magnitude of the range of the meson-nucleon field, a 200 MeV pion is restricted to an angular momentum of 2 or less; i.e. \leq a d partial wave. Gell-Mann and Watson¹ were the first to attempt to calculate an angular distribution of the differential cross-section for this reaction. Several years later Mandl and Regge² using a statistical operator approach submitted the following differential cross-section for s, p, and d-wave pions:

$$\frac{d\sigma}{d\Omega} = \frac{1}{32\pi} \{ \gamma_0 + \gamma_2 \cos^2\theta + \gamma_4 \cos^4\theta - p \sin\theta \cdot \cos\phi [\lambda_0 + \lambda_2 \cos^2\theta + (\lambda_1 \cos\theta + \lambda_3 \cos^3\theta)] \}.$$

Each coefficient generally reflects the interference of two or more partial waves. Niskanen³, using a coupled channel calculation, produced numbers for the Mandl-Regge parameters, γ_i and λ_i , for proton energies up to ~750 MeV. An extrapolation was performed on his data to permit a comparison between our experimental data and his numbers.

The unpolarized portion of the cross-section is:

$$\frac{d\sigma}{d\Omega} = \frac{1}{32\pi} \{ \gamma_0 + \gamma_2 \cos^2\theta + \gamma_4 \cos^4\theta \}.$$

The remainder of the equation is the analyzing power:

$$A_y(\theta) = \frac{1}{32\pi} p \sin\theta \{ \lambda_0 + \lambda_2 \cos^2\theta + (\lambda_1 \cos\theta + \lambda_3 \cos^3\theta) \}.$$

The γ_4 term in the unpolarized cross-section is the unique and sole contribution of d-wave pions. The λ_1 and λ_3 terms found in the analyzing power arise from s and d-wave interference. To date low counting rates and poor resolution have hampered the

detection of anything but s and p-wave pions. In the unpolarized cross-section, the $\cos^4\theta$ factor obscures observation of d-partial waves except at extreme forward and extreme backward scattering angles; a position difficult to achieve with experimental hardware. However, the odd powers of $\cos\theta$ due to d-waves in the analyzing power are asymmetric about 90° and, generally, larger in magnitude. This asymmetry of the analyzing power around 90° provides a more sensitive test for d-waves than trying to unearth a $\cos^4\theta$ dependence from the unpolarized cross-section.

The analyzing power is defined as the ratio of the left-right asymmetry to the beam polarization. When the beam polarization reverses, left and right are merely interchanged on a two-arm polarimeter. The left and right quantities are formed by taking the geometric mean of the yields from both polarimeter arms. The two-arm polarimeter avoids major sources of error inherent in previous experiments. With the two-arm polarimeter, beam intensity, the fraction of pions which decay before reaching the detector, the efficiency of the detectors, and their finite size cancel out in the analyzing power, although they are retained in the cross-section. Consequently the analyzing power data from LAMPF is an order of magnitude better than the best previous data which was taken at CERN⁴. CERN reports error of $\pm 20-30\%$ while the uncertainty in the LAMPF data runs 3-5%. The

uncertainty in the Mandl-Regge parameters are about 10%, except for λ_0 which is about 4%. The values for the coefficients λ_1 , λ_3 and λ_2 , λ_4 are plotted in Figures 1 and 2. The large values obtained for λ_1 and λ_3 indisputably demonstrate the presence of d-wave pions at this energy. The large value of λ_4 suggests the relative importance of f-wave pions.

The unpolarized cross-section for this reaction has been measured repeatedly and provides a consistency check on our data (Figure 3). Our cross-sections were found to be consistent with those of Felder⁵ (Figure 4), Richard-Serre, *et al.*,⁶ (Figure 5) and Hollas⁷.

With the enhanced precision of our measurements we conclude that current theoretical calculations are not in good agreement with the data. The surprising strength of d-wave pions remains unexplained although the spin dependent aspects of the reaction have as yet not been taken into account. Measuring the analyzing power of other nuclear reactions with the two-arm polarimeter warrants further exploitation.

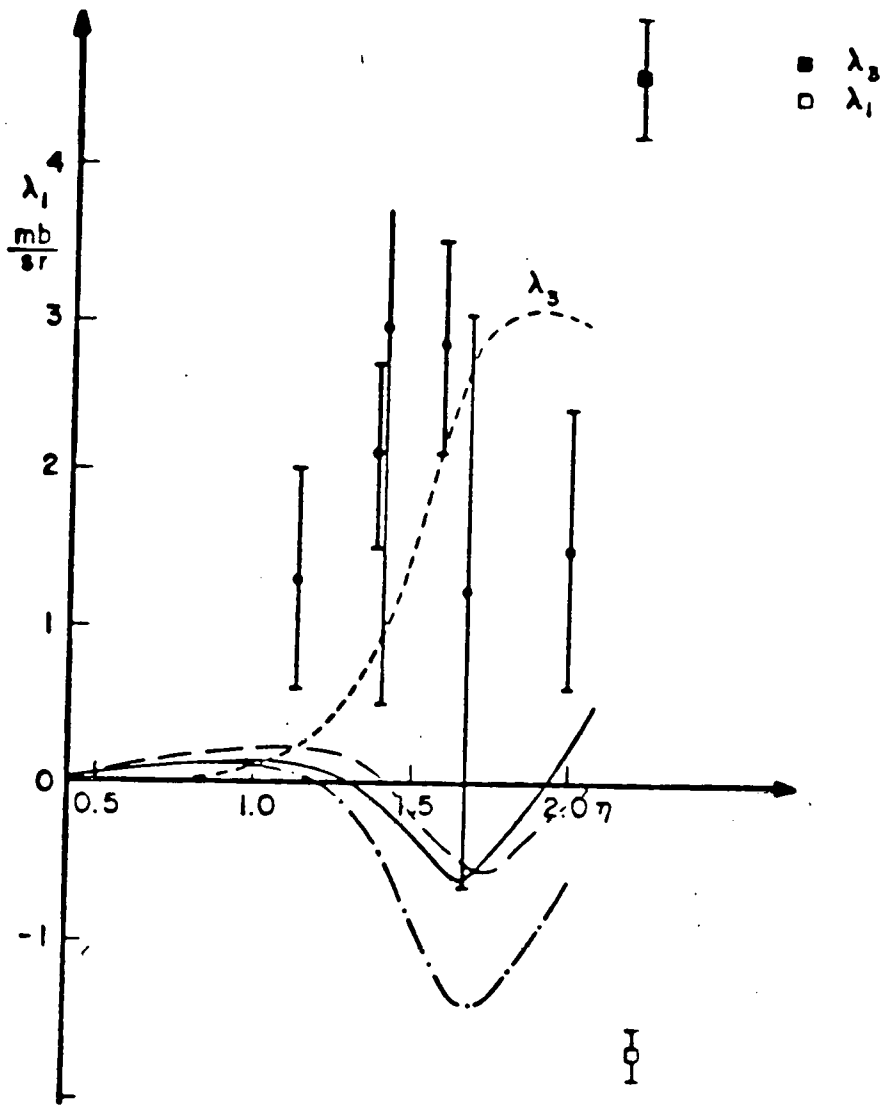


Figure 1. Polarization parameters λ_1 and λ_3 . Solid line: Galilean-invariant operator used; dashed line: non-Galilean; small dashes: higher partial waves excluding $l_\pi=3$ or $L_{pp}=3$.

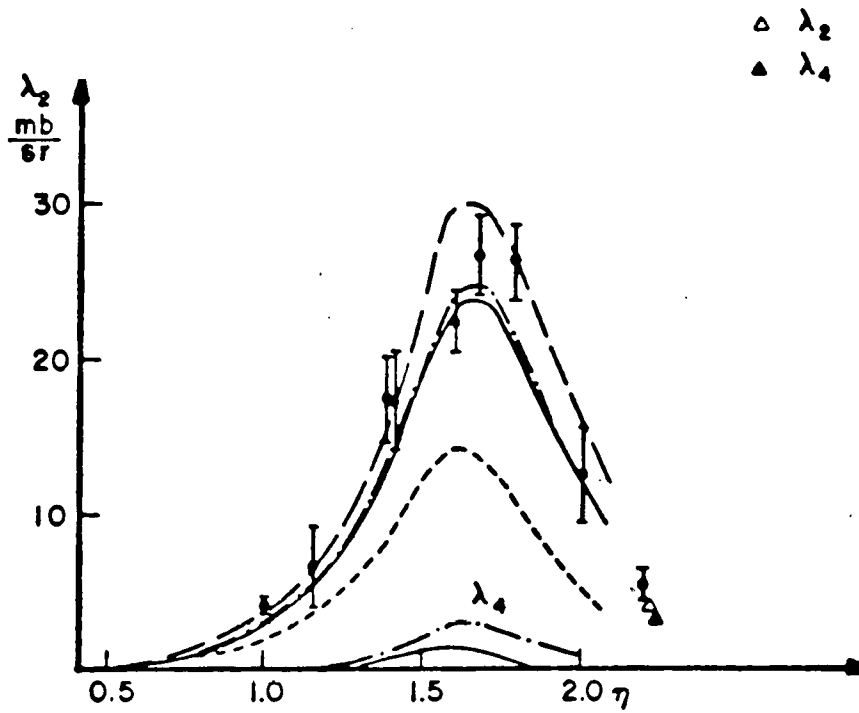


Figure 2. Polarization parameters λ_2 and λ_4 . Notation and data as in Figure 1.

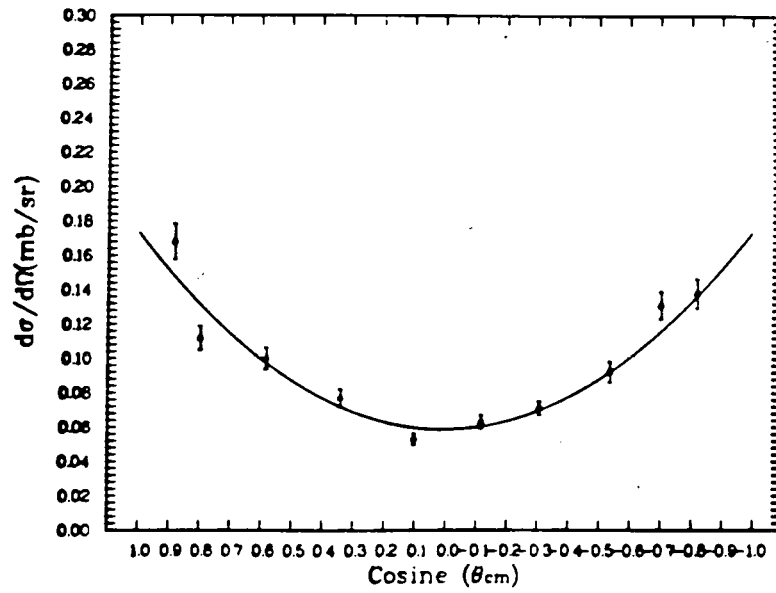
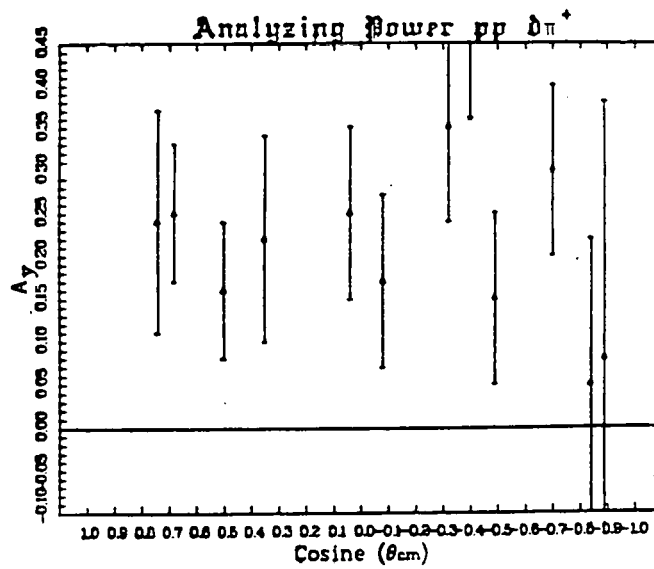


Figure 3. Differential cross section data and fit for this experiment. CERN data is shown below.



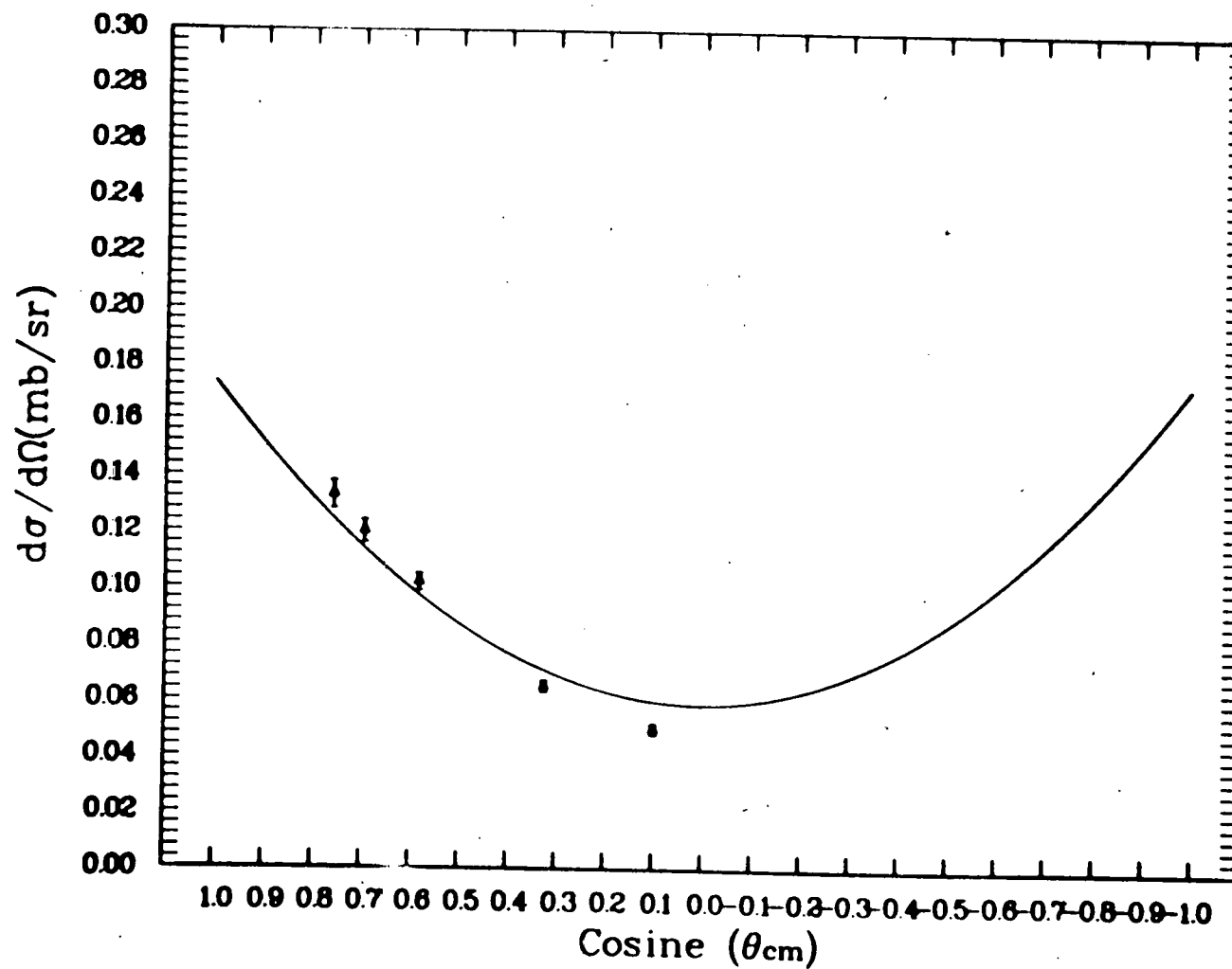


Figure 4. Data of Felder with the fit to this data.

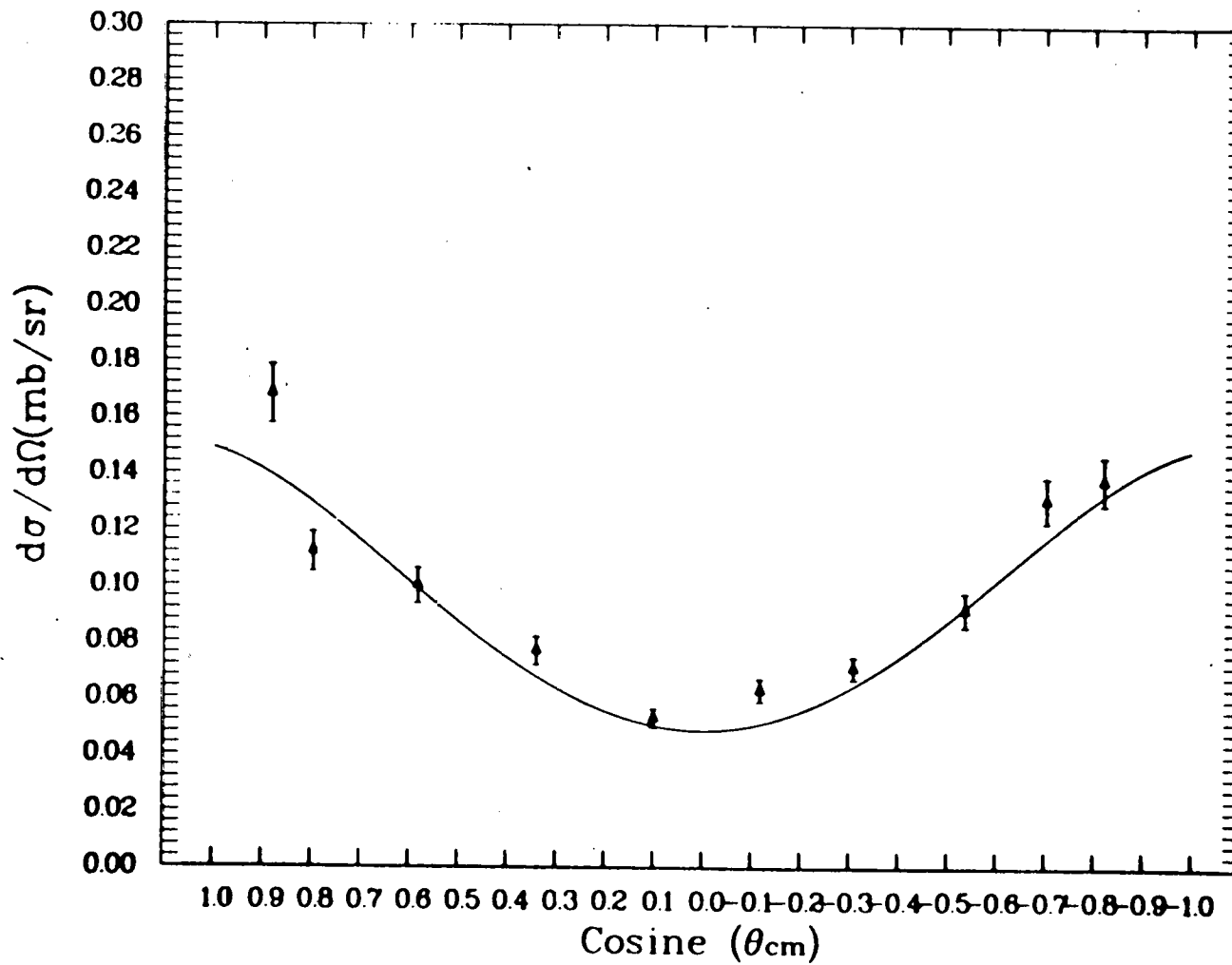


Figure 5. Fit of Richard-Serre and this data.

B. The Two-Arm Proton Polarimeter

A two-arm proton polarimeter (Figure 6) was designed to measure the analyzing power of the pion-deuteron reaction (Experiment 27). It was performed by a group consisting of members from Case Western Reserve University, The Los Alamos Scientific Laboratory, and The University of Texas at Austin. Although the experiment was not implemented with cross-sections in mind, differential cross-sections were extracted from the data as a collateral measurement.

Focused to a beam spot $< 3\text{mm}$ in diameter, 0.8 GeV protons bombarded a 10 mil CH target. Beam polarization was $\sim 70\%$ and beam current ~ 100 pA. Preliminary and conjugate particles scattered from the CH target are detected by plastic scintillators located above, below, and to the left and right of the beam. Left-right and up-down asymmetries when divided by the analyzing power give the beam polarizations perpendicular and parallel to the scattering plane, respectively. The beam line polarimeter measured the beam polarization using the analyzing power of hydrogen at 17° . Four pairs of X-Y multiwire proportional counters in a two-arm arrangement detected deuterons and positive pions. A scintillator attached to each X-Y counter registered time of flight information to aid in background

rejection. Major background elimination took place by exploiting the kinematics of the pion-deuteron system. The elapsed time between when the pion and deuteron arrive at their respective chambers is peculiar to the kinematics of the reaction and does not overlap with p-p elastic kinematics. Time of flight information was implemented via the software to discard p-p elastic events. Events were processed by a data acquisition system consisting of a chamber readout system, electronic logic, and a PDP 11/45 which recorded the data on magnetic tape for later reanalysis.

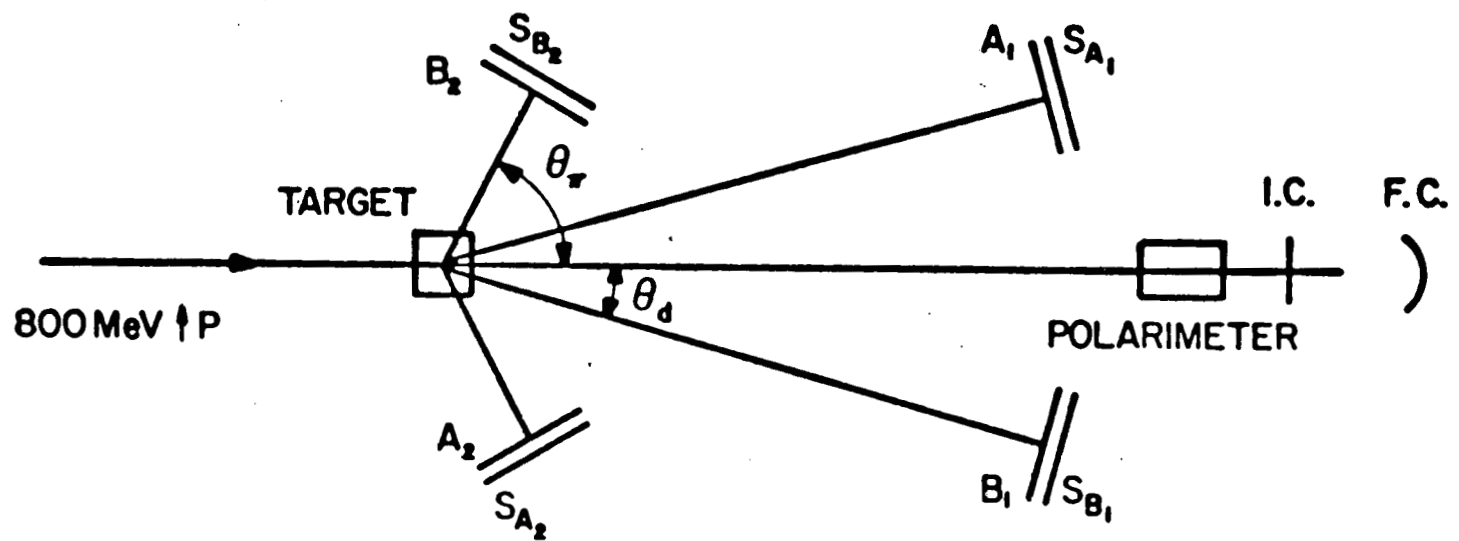


Figure 6. Experimental set-up.

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VI. PERSONNEL

(University of Texas at Austin)

Ken Boyer	student
Wil Braithwaite	faculty
Bill Cottingame	student
Steve Greene	student
Carol Harvey	student
David Holtkamp	student (graduated)
Richard Joseph	student (graduated)
C. Fred Moore	faculty
Hilde Moore	student
John Scherbak	student
Gene Smith	staff

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