MASTER

NUCLEAR-STRUCTURE STUDIES

WITH

PIONS AND HEAVY IONS

Progress Report

for the Period June 1, 1980 - May 31, 1981

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Abstract

Experiments performed at the Los Alamos Meson Physics Facility yielded very striking results. In inelastic pion scattering from ^{14}C near the $[3,3]$ resonance cross sections ratios $R = \sigma(\pi^+)/\sigma(\pi^-)$ and $R^{-1} = \sigma(\pi^-)/\sigma(\pi^+)$ were observed that are significantly larger than the free pion-nucleon values. These results were interpreted as due to strong cancellations of the neutron and proton components in the transition amplitude.

Measurements of $^{13}\text{C}(\pi, \pi')$ excitation functions between 100 and 300 MeV at two momentum transfers showed dramatically different energy dependencies for $\Delta S = 0$ and $\Delta S = 1$ transitions. They were used to derive nuclear structure information on several highly excited states. Pion data for other nuclei (^{12}C , ^{16}O , ^{40}Ca , etc.) were analyzed and information on isospin mixing, the double-charge-exchange reaction mechanism, and the excitation of collective states was extracted.

Further data were taken with a 547 MeV proton beam on ^{13}C . The data taking for the (t, t') and $(^3\text{He}, ^3\text{He}')$ reactions at the Los Alamos Van de Graaff has been completed.

The continuing studies of the heavy-ion nucleus optical potential yielded information on very systematic dependencies of the potential depths on the incident energy.

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I. Introduction

This report summarizes the work done during the period from June 1, 1980 to May 31, 1981 under contract No. DEAC02-79ER10423 between the University of Minnesota and the United States Department of Energy.

The research activities involved the use of the Energetic Pion Channel and Spectrometer, EPICS, and the High Resolution Spectrometer, HRS, at the Los Alamos Meson Physics Facility. Supplementary experiments were done at the Los Alamos Van de Graaff Laboratory.

The personnel involved were the Principal Investigator, one full time Research Associate (Dr. D. B. Holtkamp) and one Graduate Student (Susan Seestrom-Morris), both at LAMPF, a part-time Research Associate (Dr. V. Shkolnik) at the University of Minnesota and an Undergraduate Student (J. McBride) during the summer.

The work at EPICS was done in collaboration with H. W. Baer, R. L. Boudrie, C. L. Morris and H. A. Thiessen from Los Alamos and members of the University of Texas and the University of New Mexico users groups. The work at the Van de Graaff was done together with R. E. Brown, J. A. Cizewski, E. R. Flynn, C. L. Morris and George Idzorek from Los Alamos and R. J. Peterson from the University of Colorado. The (p,p') experiment on HRS was done together with J. F. Amann and R. L. Boudrie from Los Alamos. M. A. Franey from the University of Minnesota was involved in much of the work reported here and S. Chakravarti (also University of Minnesota) generated DWIA calculations for the pion experiments.

The pion work is summarized in section II, the light-ion work in section III, and the work on the heavy-ion optical potential in section IV. Publications, contributions to conferences, etc. are listed in section V.

II. Nuclear Structure Studies with Pions

1. Inelastic Scattering of 164 MeV Pions from ^{14}C (Experiment #539)

Differential cross sections were measured for inelastic scattering of 164 MeV π^+ and π^- on ^{14}C .

Large π^+/π^- asymmetries were observed, two being significantly larger than the free π -nucleon value.

The target consisted of approximately 9 g of carbon powder enriched in ^{14}C to 83%. The carbon powder had been pressed into six target cells consisting of a stainless steel frame with 0.001 in. stainless steel window foils. Each target cell had an area of 3 cm x 3 cm and contained carbon of an areal density of approximately 0.10 g/cm². Because an image of the target is created in the EPICS data analysis software it was possible to exclude the events originating from the stainless steel frames by use of software cuts. Since the size of the ^{14}C target was less than the EPICS beam spot size (approx. 8 cm x 20 cm), strips of natural graphite were placed above and below the six ^{14}C target cells. Thus both ^{12}C and ^{14}C spectra could be obtained simultaneously. Additional spectra were taken from stainless steel foils as a target. The spectra from the natural graphite and the stainless steel foils enabled us to identify contaminant peaks in the ^{14}C target spectra and to derive "cleaned-up" spectra via a channel by channel subtraction (Fig. 1 and 2). The energy resolution width was about 200 keV (F.W.H.M.).

The spectra shown in Fig. 1 and 2 still include a contaminant close to the 1^- state in ^{14}C (6.09 MeV) from ^{16}O (3^- , 6.13 MeV) and small elastic peaks from O, Mg and Cl. The ^{14}C peaks were fit using the line shape of the ^{12}C

Fig. 1. Spectra from $^{14}\text{C}(\pi, \pi')$ at $T_\pi = 164$ MeV and $\theta_{\text{lab}} = 42^\circ$; upper spectrum from (π^+, π^+') , lower spectrum: (π^-, π^-') . Only a fraction of the total spectrum is shown to emphasize the large asymmetry for the 2nd 2^+ state at 8.32 MeV.

Fig. 2. Spectra from $^{14}\text{C}(\pi, \pi')$ at $T_\pi = 164$ MeV and $\theta_{\text{lab}} = 66^\circ$.

(4.44 MeV) peak. For the known ^{14}C states the centroids of the peaks were kept fixed at values calculated from published excitation energies¹.

The most suprising feature of these data is the sharp contrast between the near equality of $\sigma(\pi^+)$ and $\sigma(\pi^-)$ for the first 2^+ state at 7.01 MeV and the highly asymmetric cross sections for the second 2^+ state at 8.32 MeV (Fig. 1). At a scattering angle ($\theta_{\text{lab}} = 42^\circ$) which is near the first maximum of normal $\Delta L = 2$ angular distributions there is no evidence for a π^- yield for the 8.32 MeV state. The experimental cross sections and errors yield a lower limit of $R > 21$ for the second 2^+ state with a confidence level of 90%. This upper limit is significantly larger than the free π -proton value of 9.

Similarly, at $\theta_{\text{lab}} = 66^\circ$ (Fig. 2), one notices among other states which exhibit π^+/π^- differences, a state at 11.67 MeV which is seen essentially only in π^- scattering and a state at 17.23 MeV which is strongly excited, but only in π^+ scattering. The lower limits for the cross section ratios are $R^{-1} > 17$ and $R > 10$, respectively. Angular distributions (not shown) for these states have maxima near 66° , i.e. like the angular distributions for known $\Delta J = 4$ transitions to unnatural parity states in ^{12}C (ref. 2), ^{13}C (ref. 3,4) and ^{16}O (ref. 5) which are due to excitations of the stretched ($d_{5/2}, p_{3/2}^{-1}$) particle-hole configuration. On the basis of this similarity to the previous pion data we propose a J^π assignment of 4^- for these states.

The near equality of $\sigma(\pi^+)$ and $\sigma(\pi^-)$ for the first 2^+ state and the large asymmetry for the second 2^+ state ($\sigma(\pi^-) \approx 0$) appears to be consistent with the present knowledge of the structure of the lowest two 2^+ states in ^{14}C . In the p-shell model calculations of Cohen and Kurath⁶ only one

low lying 2^+ state ($E_x \approx 7$ MeV) is obtained and this state can only be reached by a proton excitation. However, it has been known for some time that the two lowest 2^+ states observed experimentally ($E_x = 7.01$ MeV and 8.32 MeV) must be very strongly configuration mixed since the p-shell strength for transfer reactions⁷ and the collectively enhanced electromagnetic transition⁸ is split between the two 2^+ states. Many properties of mass 14 nuclei have been explained by the weak-coupling model¹⁰ calculations of Lie¹¹. For ^{14}C Lie assumed a total of seventeen 2^+ basis states. One of these basis states is the 2-proton hole, p-shell state of ref. 6; other basis states involve two neutrons in the s-d shell and four holes in the p-shell with either the sd-particles or p-holes (or both) coupled to 2^+ . Lie's calculation shows nearly complete mixing between the $|(p^{-2p})_{2+}>$ and $(sd^{2n})_{2+}(p^{-4})_{0+}$ basis states in the lowest two 2^+ states and relatively minor admixtures from the other configurations. Thus a reasonable approximation to Lie's wave functions for the lowest 2^+ states is

$$|2_1^+> = \alpha_1 |(p^{-2p})_{2+}> + \beta_1 |(sd^{2n})_{2+}(p^{-4})_{0+}>$$

where $i = 1, 2$ refer to the first and second 2^+ states, respectively, and $\alpha_1 = \alpha_2 = \beta_2 = \sqrt{.5}$ and $\beta_1 = -\sqrt{.5}$. Of Lie's nine 0^+ basis states only two contribute significantly to the wave function of the g.s. of ^{14}C :

$$|0_1^+> = \alpha_0 |(p^{-2p})_{0+}> + \beta_0 |(sd^{2n})_{0+}(p^{-4})_{0+}>$$

We use amplitudes $\alpha_0 = +\sqrt{.84}$ and $\beta_0 = -\sqrt{.16}$ which are somewhat different from Lie's values but more in line with other work¹². For $[3,3]$ resonance dominance and when the impulse approximation is valid $\sigma(\pi^-) \propto |3A_n + A_p|^2$ and $\sigma(\pi^+) \propto |A_n + 3A_p|^2$ where A_n and A_p are the neutron and proton components

of the transition amplitude. If effective charges δ_p and δ_n are used to account for neglected terms in the wavefunctions we have

$$\sigma(\pi^-) \propto |(3 + 3\delta_p + \delta_n)A_n + (1 + \delta_p + 3\delta_n)A_p|^2$$

and
$$\sigma(\pi^+) \propto |(1 + \delta_p + 3\delta_n)A_n + (3 + 3\delta_p + \delta_n)A_p|^2,$$

(See. eq. 12 of ref. 9, extended to include both neutron and proton amplitudes.)

It is clear that the opposite signs of the (sd^2) components in the wave functions of the two 2^+ states will cause constructive interference between the neutron and proton contributions to the transition for one 2^+ state and destructive interference for the other - depending on the signs of the matrix elements of the particle-hole operator. S. Chakravarti derived these matrix elements using the weak-coupling wave functions of ref. 10 for the (sd^2) and (p^{-2}) parts of the ground and excited states in ^{14}C . Preliminary DWIA calculations with the Argonne DWIA code using these matrix elements do indeed show very strong cancellation effects. Use of an effective charge $\delta_p = \delta_n = 0.4$ and an (sd^2) admixture in the ground state of $\beta_0 = 0.4$ reproduce the experimental ratios very well but predict absolute $\sigma(\pi^+)$ cross sections for the 2_2^+ state about a factor of two too large. Work on this problem is in progress.

The data for the two proposed 4^- states at 11.67 and 17.23 MeV (Fig. 2) are also strongly suggestive of cancellation effects. In any simple model several 4^- , $T = 1$ states are expected with large components of the stretched $(p_{3/2}^{-1}d_{5/2}^1)$ configuration. The 4^- state lowest in energy should have a large overlap with a state formed by a $d_{5/2}$ neutron coupled to a $3/2^-$, $T = 1/2$ ^{13}C core (see ref. 11). This state would be reached mainly by a neutron particle-hole excitation from a $3/2^-$, $T = 1/2$ core component in the ground state of ^{14}C . The experimental ratio for the lower 4^- state at

11.67 MeV, $R^{-1} > 17$, is larger than the free pion-neutron value of $R^{-1} \approx 9$, indicating the presence of small contributions from proton particle-hole excitations to the transition density amplitude with a sign opposite to the one of the principal neutron particle-hole excitation.

Although the lower limit of $R > 10$ for the other prominent 4^- state at 17.23 MeV is consistent with a pure proton excitation ($R \approx 9$) we reject such an interpretation since it would lead to a state strongly mixed in isospin which is unlikely. A 4^- state of simple $[p_{3/2}^{-1}d_{5/2}^1]$ structure is expected around this energy due to coupling of a $d_{5/2}$ nucleon to a $T = 3/2$, mass 13 core (^{13}C or ^{13}B). This state would be reached from a $T = 3/2$ core component in the g.s. by both proton and neutron excitations with a resulting ratio of $R \approx 3$. The experimental value $R > 10$ implies contributions from components in the g.s. and the 4^- state other than the ones mentioned above. Kurath has shown in a shell model calculation¹³ similar to the one of ref. 14 that the g.s. of ^{14}C does have comparable amounts of $T = 1/2$ and $T = 3/2$ mass 13 cores. In his model the lower 4^- state (predicted at 12.7 MeV) is reached mainly by a neutron particle-hole excitation from the $T = 1/2$ core component in the g.s. Another 4^- state (predicted at 16.9 MeV) is reached by a mixture of neutron and proton excitations involving both $T = 1/2$ and $T = 3/2$ cores. Cross section ratios estimated²⁴ for these two states are in good agreement with our data for the 11.67 and 17.23 MeV states, but estimated absolute cross sections are about a factor of two too large.

In summary, cross section ratios larger than the free pion-nucleon values were observed for the first time in inelastic pion scattering on ^{14}C at 164 MeV. An interpretation of the results in terms of a strong cancellation of the neutron and proton components of the transition amplitudes is suggested. Thus this experiment gives a particularly convincing example for the high sensitivity of inelastic scattering of π^+ and π^- to the neutron/proton structure of nuclear transitions. A manuscript is now being prepared for publication.

2. Excitation Functions for Inelastic Pion Scattering from ^{13}C between 100 and 300 MeV (Experiment # 510)

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

The target was a 15 cm x 23 cm sheet of carbon, 210 mg/cm^2 thick, enriched in ^{13}C to 99%, and covered on both sides by thin ($\approx 1 \text{ mg/cm}^2$) Kapton foils. The energy resolution width was about 250 keV (FWHM). At each energy the scattering angles were chosen to keep the momentum transfer fixed at either $1.1 \text{ \AA fm}^{-1}$ or $1.4 \text{ \AA fm}^{-1}$. The former value is close to the

first maximum in the angular distribution for a $\Delta L = 2$ transition and the latter is close to the maximum in the angular distribution for the strongly π^- enhanced transition to a state at 9.5 MeV^{3,4}.

The pion-nucleon scattering amplitude can be written in the following form if the interaction is dominated by the [3,3] resonance¹⁵:

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

where $k(k')$ is the pion momentum before (after) the collision, θ is the scattering angle in the pion-nucleon c.m. frame, $\vec{\sigma}$ is the spin operator for the nucleon, $\hat{n}$ is the normal to the scattering plane, and the coefficient $\alpha(k)$ is energy dependent. Only the operator $\vec{\sigma} \cdot \hat{n}$ can lead to a spin transfer ($\Delta S = 1$). Siciliano and Walker have shown that a similar expression holds for pion-nucleus inelastic scattering¹⁶. In their formalism, the differential cross section for pion-nucleus inelastic scattering in the fixed scatterer approximation is given by:

$$\alpha(\theta) = F(E) [4 M^2(q, E) \cos^2 \theta + S^2(q, E) \sin^2 \theta]$$

assuming dominance of the [3,3] resonance, the validity of the impulse approximation, and a one-step reaction mechanism. Here E is the pion energy, q is the momentum transfer, θ is the scattering angle in the pion-nucleus laboratory frame, and $M(q, E)$ and $S(q, E)$ are the spin-independent and spin-dependent form factors, respectively. $F(E)$ contains the energy-dependence of the pion-nucleon amplitudes in the laboratory frame and phase space factors. The energy dependences of the form factors $M(q, E)$ and $S(q, E)$ are due to distorted wave attenuation effects and have been estimated to be very similar for values of $q=q_0$, i.e. near the maxima of the form factors.

Thus this energy dependence can be factored out and combined with $F(E)$ to yield $\Gamma(E)$ so that at constant $q=q_0$ (ref. 16)

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

Both $M(q_0)$ and $S(q_0)$ contribute to natural parity transitions, but they are usually dominated by $M(q_0)$. Only the spin-dependent form factor can contribute to $\Delta S = 1$ transitions (if Fermi motion corrections are neglected).

The scattering angle θ is a simple function of the incident energy or wave number k , i.e. $\theta = 2 \sin^{-1}(q/2k)$. To keep the momentum transfer constant at the q value where the cross sections for the transitions of interest have maxima, the scattering angle needs to be decreased from about 90° at $T_\pi = 100$ MeV to about 32° at $T_\pi = 300$ MeV. (Due to its large width the $[3,3]$ resonance is dominant over this whole energy range.) Thus the energy dependence of $\sigma(\theta)$ for $\Delta S = 1$ transitions and $\Delta S = 0$ transitions measured at constant momentum transfer will be very different simply due to the difference between the $\sin^2\theta$ and $\cos^2\theta$ functions. The energy dependences of the $\sin^2\theta$ and $\cos^2\theta$ functions are in fact expected to dominate the shapes of the excitation functions since $\Gamma(E)$ depends only relatively weakly on the energy for constant q . Consequently, the cross sections for $\Delta S = 1$ transitions should decrease with increasing energy since $\sin^2\theta$ decreases between 100 MeV ($\theta \approx 90^\circ$) and 300 MeV ($\theta \approx 32^\circ$). In contrast, the cross sections for $\Delta S = 0$ transitions should increase with increasing energy due to the associated $\cos^2(\theta)$ dependence. Indeed, the work of Moore et al.¹⁷ and Cottingham et al.¹⁸ showed that the transitions to known natural and unnatural parity states in $^{12}\text{C}(\pi, \pi')$ have dramatically different energy dependences and indicated the presence of previously unknown unnatural parity transitions.

In the present work the $(\pi^+, \pi^{+'})$ cross sections for the transitions to the strongly excited $3/2^-$ state (3.68 MeV), and the unresolved $5/2^-$, $7/2^+$ doublet (7.5 MeV), were measured at $q = 1.1 \text{ \AA fm}^{-1}$ and found to increase uniformly with energy (Fig. 3). The $3/2^-$ and $5/2^-$ states are collectively enhanced and predicted to be dominated by the $\Delta L = 2$, $\Delta S = 0$ transition amplitude¹⁹. At $q = 1.1 \text{ \AA fm}^{-1}$ the cross sections measured for the doublet at 7.5 MeV are expected to be due mostly to the $5/2^-$ state and thus the excitation function for this group should show the features of a $\Delta S = 0$ transition like the excitation function for the transition to the $3/2^-$ state. Indeed, for both states the simple $\cos^2\theta$ relation (Fig. 3, broken lines) predicts the trend of the data quite well. A distorted wave impulse approximation (DWIA) calculation of the $3/2^-$ state using the code DWPI of Eisenstein and Miller²⁰ with a simple collective form factor reproduces the shape of the excitation function in detail (Fig. 3, solid line). The relatively small differences between the $\cos^2\theta$ function and the DWIA result verify the claims made above regarding the weakness of the energy dependence of Γ .

The $(\pi^-, \pi^{-'})$ excitation function for the transition to the 9.5 MeV state was measured at $q = 1.4 \text{ \AA fm}^{-1}$ and found to decrease uniformly with energy (Fig. 1), in sharp contrast to the data for the $\Delta S = 0$ transitions discussed above. The energy dependence is very well accounted for by $\sin^2(\theta)$ (dash dotted line).

It has been proposed that this state is the $9/2^+$ member of a weak-coupling multiplet²¹ based on a $1d_{5/2}$ neutron coupled to the first excited 2^+ state in ^{12}C . In this model the large π^- asymmetry²² $A = (\sigma(\pi^-) - \sigma(\pi^+)) / (\sigma(\pi^-) + \sigma(\pi^+)) = -0.8 \pm 0.2$ can be explained as due to a pure neutron $1p_{3/2} \rightarrow 1d_{5/2}$ particle-hole excitation. The shell model

Fig. 3. Excitation functions for $^{13}\text{C}(\pi^+, \pi^+')$ to the 3/2⁻ (3.68 MeV) and 5/2⁻ (7.55 MeV) states measured at $q = 1.1 \hbar \text{fm}^{-1}$ and for $^{13}\text{C}(\pi^-, \pi^-)$ to the 9/2⁺ (9.50 MeV) state measured at $q = 1.4 \hbar \text{fm}^{-1}$. The dashed (dash-dot) lines are the $\cos^2\theta$ ($\sin^2\theta$) dependences arbitrarily normalized to the data at 180 MeV. The solid line is the result of a DWIA calculation for the 3/2⁻ state.

calculations of Millener and Kurath¹⁴ predict a $9/2^+$ state at 9.5 MeV which has a very large overlap with the weak-coupling state. The DWIA calculations of Lee and Kurath⁴ using the Millener and Kurath wave functions reproduce not only the π^- enhancement very well but also the absolute cross sections³ for exciting this state to within about 20%. According to this model the $9/2^+$ state is reached solely by an unnatural parity transition with a total angular momentum transfer $\Delta J = 4$, an orbital angular momentum transfer $\Delta L = 3$, and a spin transfer $\Delta S = 1$. The experimental excitation function for this state from the present work is characteristic of a $\Delta S = 1$ transition in excellent agreement with the shell model calculation^{4,14}.

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

Four states, or groups of states, in the excitation energy region from 12 to 24 MeV were found to be strongly excited at large momentum transfer. Their angular distributions are fairly structureless and peak at large angles characteristic of a large angular momentum transfer to high spin states³. The centroids of these groups are at 16.05, 17.92, 21.38, and 21.60 MeV. Their excitation functions at $q = 1.4$ fm^{-1} are very similar to that for the $9/2^+$ state at 9.50 MeV and they are also very well described by $\sin^2\theta$ (Fig. 4). Thus the transitions to these states must be dominated by $\Delta S = 1$. The 16.05 MeV state is π^+ enhanced, $A = +0.6 \pm 0.2$ (ref.22), in agreement with the shell model prediction^{4,14}

Fig. 4. Excitation functions for $^{13}\text{C}(\pi^{\pm}, \pi^{\pm'})$ to states at 9.50 and 21.60 MeV (with π^-) and at 16.05, 17.92, and 21.38 MeV (with π^+) measured at $q = 1.4 \hbar \text{ fm}^{-1}$. The solid lines are simple $\sin^2\theta$ dependences.

for a $9/2^+$ state close to 16 MeV. The complex close to 21.5 MeV peaks at 21.38 MeV in π^+ scattering and at 21.60 MeV in π^- scattering. The state or group of states at 17.92 MeV is excited about equally by π^+ and π^- . An interpretation of these results in terms of shell model predictions is difficult because of the large number of states involved. The 21.5 MeV complex probably contains several $7/2^+$ and $9/2^+$ states. Furthermore, the $T = 1/2$ and $T = 3/2$ states at these energies are most likely mixed in isospin. Isospin mixing was not included in ref. 10 but its importance is suggested by the similarity of the pion spectra²² close to 21.5 MeV in ^{13}C with those² close to 19 MeV in ^{12}C .

The 180° electron scattering data of ref. 23 and 24 are in agreement with our $\Delta S = 1$ assignments for some of these transitions. They found M4 transitions to states at 9.49, 16.06, and 21.43 MeV but do not see any significant strength at ~ 17.9 MeV. A comparison of the different excitation strengths from $(\pi^+, \pi^{+'})$, $(\pi^-, \pi^{-'})$, and (e, e') allows conclusions about the isospin transfer ΔT since the transverse (e, e') form factor is dominated by $\Delta T = 1$. The near equality of $\sigma(\pi^-)$ and $\sigma(\pi^+)$ for the group at 17.92 MeV suggests a pure isospin transfer of either $\Delta T = 0$ and $\Delta T = 1$, but the lack of any significant M4 strength from (e, e') strongly supports a pure $\Delta T = 0$ transitions. The excitation energy of one of the strong M4's from (e, e') , $E_x = 21.43 \pm 0.03 \text{ MeV}$ ²⁴, is close to the centroid of the peak seen in $(\pi^+, \pi^{+'})$. This suggests a concentration of the $\Delta T = 1$ strength in the lower energy part of the 21.5 MeV complex. A precise measurement of peak shapes and peak positions for both (π, π') and (e, e') would aid considerably a more detailed analysis of the 21.5 MeV region.

In summary, these data have demonstrated the utility of measurements of excitation functions of inelastic pion scattering in the identification of $\Delta S = 1$ transitions. This technique has been used to confirm that the transition to the $9/2^+$ state at 9.5 MeV involves $\Delta S = 1$ and to identify four $\Delta S = 1$ transitions to states in the region from 12 to 24 MeV in ^{13}C . Knowledge of whether a transition is dominated by $\Delta S = 1$ is very useful for tests of model predictions. A manuscript has been prepared recently and submitted for publication.

3. Elastic and Inelastic Scattering of π^+ and π^- from ^{13}C at 162 MeV (LAMPF Experiment # 452)

Part of this work has been discussed in last year's report and a detailed description was recently given by Susan J. Seestrom-Morris in her Ph.D. Thesis (ref. 24). We present here only a brief discussion of some of the recent results.

a. Elastic Scattering

The finalized elastic data are presented in Fig. 5. These data were analyzed using the code DWPI of Eisenstein and Miller²⁰. A potential of Kisslinger form was used but protons and neutrons were allowed to have different density distributions. Two sets of potential strength parameters were derived from pion-nucleon phase shifts.

We quote from ref. 3: "Set I was calculated within the code NDWPI, using the approximation of Auerbach, et al.²⁵ for the transformation from the pion-nucleon center-of-mass system to the pion-nucleus center-of-mass system. The second set was generated using the method of Cottingham, et al.,²⁶ where the pion nucleon phase shifts are evaluated at an energy 30 MeV less than the corresponding incident pion energy." Use of the second set resulted

Fig. 5. Elastic scattering cross sections for $^{13}\text{C} + \pi^{+}$ and $^{13}\text{C} + \pi^{-}$ at $T_{\pi} = 162 \text{ MeV}$.

in better fits to the data than use of the first (Fig.6). For the density distributions we assumed two-parameter p-shell Gaussian distributions and a three-parameter Fermi distribution (Table I). The curves in Fig. 6 were obtained with the p-shell Gaussian labelled ρ_I with r.m.s. radius $\langle r^2 \rangle^{1/2} = 2.305$ fm. Fig. 7 shows the results for another p-shell Gaussian (ρ_{III} ; $\langle r^2 \rangle^{1/2} = 2.28$ fm) and a three parameter Fermi distribution (ρ_{II} ; $\langle r^2 \rangle^{1/2} = 2.28$ fm). For both calculations in Fig. 7 the "energy shifted" $V(r)$ was used. "The two densities ρ_{II} and ρ_{III} produce results that agree equally well with the data out to the second maximum. The agreement is much better near the second minimum and third maximum for ρ_2 than it is for ρ_3 . Since both distributions have the same rms radius, the calculations show some sensitivity to the details of the density distribution. This is probably due mostly to the difference between the radial fall-off at large radii of the two distributions. Since pions are strongly absorbed they are particularly sensitive to small differences in the surface of the nucleus.

The quality of the agreement of the calculations (done with equal r.m.s. radii for protons and neutrons) with both the π^+ and π^- data shows no indication that the neutron distribution has an r.m.s. radius different from the proton distribution. If the neutron r.m.s. radius is increased from 2.28 to 2.35 fm the position of the first minimum in the angular distribution is shifted by only about 1° . The r.m.s. radius needed to reproduce the position of the first minimum depends slightly on the energy shift used in calculating the optical potential. It seems that a systematic study of elastic scattering at many energies and from many nuclei needs to be done before reliable values can be extracted for

Fig. 6. Elastic data and optical model fits with a standard potential and an "energy-shifted" potential (see text) for $^{13}\text{C} + \pi$.

Fig. 7. Elastic data and optical model fits using two different density distributions (see text).

Table 1 : Neutron and Proton Density Distribution Parameters

label	c_p (fm)	c_n (fm)	$\langle r^2 \rangle_p^{1/2}$ (fm)	$\langle r^2 \rangle_n^{1/2}$ (fm)
$\rho_I^{(a)}$	1.565	1.549	2.305	2.305
$\rho_{II}^{(b)}$	2.40	2.40	2.28	2.28
$\rho_{III}^{(a)}$	1.548	1.532	2.28	2.28

(a) Two-parameter p-shell Gaussian distribution:

$$\rho(r) = \rho_0 \left(1 + \alpha \frac{r^2}{c^2} \right) \exp \left(- \frac{r^2}{c^2} \right)$$

where $\alpha = \frac{Z-2}{3}$ for protons and $\alpha = \frac{N-2}{3}$ for neutrons

(b) Three-parameter Fermi distribution:

$$\rho(r) = \rho_0 \left(1 + \exp \frac{r-c}{z} \right)^{-1} \left(1 + \frac{wr^2}{c^2} \right)$$

where $z = 0.41$ fm and $w = -0.16$ both for protons and neutrons.

the differences between the neutron and proton distributions." It also seems clear that a theoretical justification needs to be found for the energy shift method²⁶.

We have also investigated the effect of the "inelastic contribution" to the elastic scattering. Since ^{13}C is an odd-mass nucleus, transitions can occur between, e.g., the 0p-1h and 2p-1h components in the ground state wavefunction. Using the transition density of Kurath¹⁹ we found only a negligibly small contribution to the elastic cross sections within the angular range covered by this experiment (DWIA calculations done by S. Chakravarti).

b. Inelastic Scattering; Collective Model

A collective model analysis of the enhanced quadrupole transitions to the $3/2^-$ (3.68 MeV) and $5/2^-$ (7.55 MeV) states and the octupole transition to the 11.82 MeV state was done. We quote from ref. 3 :

"The calculations were performed with the optical potentials and transition densities (of the previous section) with a version of the code DWPI²⁰, called NDWPI, which had been modified by R. Eisenstein to use separate deformation parameters, β_n and β_p , for the neutron and proton density distributions. Calculations were first done with $\beta_p = \beta_n = 1$ and then β_p and β_n were adjusted to reproduce the experimental peak cross sections by solving the following equations:

$$\begin{aligned} R^+ &= (3Z\beta_p + N\beta_n)^2 / (3Z + N)^2 \\ R^- &= (Z\beta_p + 3N\beta_n)^2 / (Z + 3N)^2 \end{aligned} \quad \text{Eq. II.3.1.}$$

where R^+ and R^- are defined by:

$$R^\pm = \frac{\sigma^\pm(\text{exp})}{\sigma^\pm(\text{DW})}$$

Here $\sigma^\pm(\text{DW})$ are the cross sections calculated with $\beta_p = \beta_n = 1$. After β_p and β_n had been determined from Eq. II.3.1 DWIA calculations were done with these values of β_p and β_n and the good fits generated with these calculations are presented in Fig. 8. The angular distributions for the strongly excited 11.82 MeV state are suggestive of $\Delta l = 3$ and its energy is close to the energy of the collectively enhanced 3^- state at 9.63 MeV in ^{12}C . Thus the spin of this state is suggested to be either $5/2^+$ or $7/2^+$ or it is a $5/2^+/7/2^+$ doublet. The solid curves correspond to density ρ_{II} and the dashed curves to density ρ_{III} . The quality of the agreement between the calculations and the data is

Fig. 8. Inelastic data and collective model predictions for strongly excited states in ^{13}C .

better for ρ_{III} than for ρ_{II} for all three states. For the $3/2^-$ and $5/2^-$ states, the shape of the calculations reproduces the experimental shapes quite well. For the 11.82 MeV state the agreement is not as good, especially not at angles larger than 75° .

In collective model analyses of inelastic scattering it is customary to quote the deformation length, βR , obtained from the analysis. The parameter R is the undeformed value of the radius parameter that is given an explicit angular dependence. However, the interpretation of the "deformation lengths" obtained in terms of static or dynamic deformations of the nuclear shape can be misleading. In cases, such as the $5/2^-$ state, where the proton and neutron deformation lengths were found to be very different it would imply strongly different shapes for the neutron and proton distributions in the nucleus. This is not at all reasonable. The justification for the use of this model is that it provides a very simple procedure to generate a semi-realistic, surface-peaked transition density that can be used to extract estimates of the relative strengths of the contributions of neutrons and protons to the transition." Quantitative details of these studies can be found in ref. 3

c. Inelastic Scattering, Microscopic Model.

Of the quite complete comparison of the inelastic data with the predictions of Lee and Kurath^{4,19} we show here only a sample of a few weakly excited states for which theory does only a poor job. We quote from ref. 3

"In Figure 9 three sets of angular distributions (π^+, π^+ and π^-, π^-) are presented, one each for the states at 3.09 MeV ($1/2^+$), 3.85 ($5/2^+$), and 8.86 MeV ($1/2^-$). In contrast to the results for the first $9/2^+$ state at 9.5 MeV (see last year's report) the agreement between the calculations and the data is not very good for the $1/2^+$ state at 3.09 MeV. According to Lee and Kurath⁴ the π^- transition is dominated by the ($L = 1, S = 0$) transition density amplitudes, while for π^+ the ($L = 1, S = 0$) and ($L = 1, S = 1$) amplitudes are of comparable magnitude. The excitation of the ($L = 1, S = 0$) strength is inhibited for both π^+ and π^- by the destructive interference between the amplitudes for $(1p) \rightarrow (1d)$ and $(1p) \rightarrow (2s)$ excitation. Most of the $(1p) \rightarrow (2s)$ amplitude is $1p_{1/2}$ to $2s_{1/2}$ which is almost pure neutron. The differences in the effect of the interference on the π^+ and π^- scattering results in quite different theoretical angular distributions. However, the quality of the data is not good enough to say whether the π^+ and π^- angular distribution have different shapes. Nevertheless, it is apparent that the calculated π^+ cross sections are a factor of 3 to 5 smaller than the experimental cross sections. The magnitude of the π^- cross section, however, is consistent with the data. The gross underestimation of the π^+ cross section may be due to the fact that the ground state of ^{13}C as described by the Cohen and Kurath wave functions has too few protons in the $1p_{1/2}$ orbit. An increase in the $1p_{1/2}$ proton components in the ground state would increase the $1p_{1/2}$ to $2s_{1/2}$ proton amplitude, decrease the $1p_{3/2}$ to $1d_{5/2}$ amplitude, and result in less destructive interference for π^+ scattering. Thus the π^+ cross section would increase relative to the π^- cross section. Components in the ^{13}C ground state with two particles in

Fig. 9. Inelastic data and microscopic model predictions (ref. 4, 19) for weakly excited states in ^{13}C .

the (2s1d) shell would also increase the cross sections and make the neutron and proton components of the transition density more equal.

The angular distributions in the middle of Fig. 9 are the calculations and the π^+ and π^- data for the $5/2^+$ state at 3.85 MeV. The calculations⁴ successfully predict the positions of the maxima and minima in the angular distributions but the absolute magnitude is too low for both π^+ and π^- . In addition, the calculated ratio $\sigma(\pi^-)/\sigma(\pi^+)$ is 4.2, compared to the experimental value of ≈ 2 . As for the $1/2^+$ state, the transition to this state is not as neutron dominated as the shell model predictions indicate.

The last set of angular distributions (bottom of Figure 9) are for the $1/2^-$ state at 8.86 MeV. This transition is very weak and the error bars are quite large. The calculations fail to reproduce both the absolute cross sections and the π^+/π^- ratio. The predicted π^+/π^- ratio is about ten, whereas the experimental ratio is between one and two. For π^+ the calculated angular distribution is shifted out of phase with respect to the data. The p-shell model⁴ predicts proton amplitudes much larger than the neutron amplitudes only for the ($L = 0$, $S = 1$) amplitude. For the ($L = 2$, $S = 1$) amplitude the proton to neutron ratio is about two." Thus a better fit to the data could be obtained with a larger ($L = 2$, $S = 1$) amplitude. Of course, the weakness of this transition makes it very likely that two-step processes contribute.

Since the optical potential used by Lee for these calculations does not fit our elastic data very well we plan to repeat the microscopic analysis with our potential sets (see proposal). Nevertheless, since Lee used the same set consistently throughout the p-shell we consider the comparison of the data with these calculations worth publishing and a manuscript is presently being prepared.

4. Inelastic Scattering of π^+ and π^- from ^{16}O (LAMPF Experiments # 369 and # 229)

The $^{16}\text{O}(\pi,\pi')$ data from this experiment have now been published⁵.

We were very pleased to see that recent (e,e') and (p,p') data were analyzed³⁰ very successfully when the transition densities were based on the pion work. Within the framework of the DWIA, the proton and electron results are predicted very well by the lp-lh transition amplitudes for the 4^- states, once the isospin mixing derived from the pion data is properly taken into account. This is a very encouraging result because it implies that consistent and reliable conclusions about nuclear structure can be obtained through comparing pion, proton, and electron excitations of nuclear states. This unification of the three most common intermediate energy probes within the framework of the DWIA is likely to be a fruitful approach in the future.

5. Other Studies Using Pion Beams

The following three investigations were done with Susan Seestrom-Morris and/or D. B. Holtkamp as participants. Manuscripts have now been submitted for publication and we quote here only the names of all collaborators and the abstract of the paper.

a. Pion Inelastic Scattering to Low Lying States in ^{12}C and ^{40}Ca .

Christopher L. Morris, Los Alamos Scientific Laboratory,
Kenneth C. Boyer, C. Fred Moore, Carol J. Harvey, K. J.
Kallianpur, Ingrid B. Moore, and Peter A. Seidl, University
of Texas at Austin, Susan J. Seestrom-Morris and D. B. Holtkamp,
University of Minnesota, Steven J. Greene and William B.
Cottingham, New Mexico State University.

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

- b. Measurements of Isospin Mixing Between the 1^+ Doublet in ^{12}C Using Pion Inelastic Scattering. C. L. Morris, R. L. Boudrie and J. Piffaretti, Los Alamos Scientific Laboratory, W. B. Cottingham, W. J. Braithwaite, S. J. Greene, C. J. Harvey, D. B. Holtkamp, and C. Fred Moore, University of Texas at Austin, S. J. Seestrom-Morris, University of Minnesota.

Abstract: Pion inelastic scattering has been used to extract the off-diagonal charge dependent matrix element H_{01} between the $J^\pi = 1^+$ doublet of states at 12.71 (T = 0) and 15.11 (T = 1) MeV in ^{12}C . The reported measurements yield a value, $H_{01} = 148 \pm 29$ keV, in good agreement with recent electromagnetic measurements.

- c. Interference Effects in Pion Double Charge Exchange. S. J. Greene, D. B. Holtkamp, W. B. Cottingham, and C. Fred Moore, University of Texas at Austin, G. R. Burleson, New Mexico State University, C. L. Morris, and H. A. Thiessen, Los Alamos Scientific Laboratory, H. T. Fortune, Los Alamos Scientific Laboratory and University of Pennsylvania.

Abstract: Pion double charge exchange (π^+, π^-) has been measured using targets of ^{16}O and ^{18}O from 80 to 292 MeV at a laboratory angle of 5° . The cross section for the double-analog transition is explained in terms of a direct double-analog amplitude and a two-step non-analog amplitude.

III. Nuclear Structure Studies with Light Ions.

1. Scattering of Polarized Protons from ^{13}C at 547 MeV (LAMPF Experiment # 580)

Microscopic model calculations^{4,19} for inelastic pion scattering on ^{13}C have been very successful for the strongly excited states but failed for several weak transitions. To allow an additional test of the microscopic wave functions we have begun an experiment with polarized protons at HRS. Data were taken for differential cross sections and analyzing powers for many states in ^{13}C . The data are now being analyzed using the Love-Francy effective interaction and the transition densities of Lee and Kurath. We are trying to reach a consistent description of our pion and proton data as well as of the electron data from Bates and the 800 MeV proton data of Blanpied et al.²⁸

2. Isospin Structure of Nuclear Excitations from a Comparison of the (t,t') and ($^3\text{He}, ^3\text{He}'$) Reactions at Low Energies.

During the last year only a few data points had been taken for inelastic scattering of ^3He from ^{13}C and at an energy lower than originally planned because of difficulties with the accelerator. We have now successfully run at the desired energy ($E(^3\text{He}) = 25.4$ MeV) and both elastic and inelastic data have been taken. In addition we have measured elastic scattering

cross sections for $^{13}\text{C} + t$ at 23 MeV when the three-stage mode of the accelerator became operational. Data reduction has been completed.

We have analyzed both elastic data sets ($^3\text{He} + ^{13}\text{C}$ and $t + ^{13}\text{C}$) with an optical model and are now applying these potential sets in DWBA and CCBA calculations for the inelastic transitions. Previously we had shown in a CCBA calculation using an optical potential from the literature that the near equality of the (t, t') and $(^3\text{He}, ^3\text{He}')$ cross sections to the $9/2^+$ state at 9.5 MeV can indeed be understood as mainly due to two-step reaction processes. (This state showed the large asymmetry in the (π, π') experiment.) Large $t/^3\text{He}$ asymmetries for other states are quite consistent with the pion work. It seems that the $(2^+) \times (d_{5/2})$ structure of the $9/2^+$ state at 9.5 MeV makes it particularly susceptible to an excitation by a two-step process induced by t and ^3He . Since nucleon pick-up followed by nucleon stripping is a very unlikely process in (π, π') as opposed to (t, t') and $(^3\text{He}, ^3\text{He}')$ the success of the single-step DWIA in reproducing the $9/2^+$ cross sections from (π, π') is consistent with the failure of the DWBA for the (t, t') and $(^3\text{He}, ^3\text{He}')$ reactions leading to the same state. Analysis of the data using the new potential sets is in progress.

IV. Nuclear Structure Studies with Heavy Ions (reported by V. Shkolnik)

1. The $^{16}\text{O} + ^{28}\text{Si}$ System; Energy Dependence of the Optical Potential, Radial Wave Functions, Parity-Dependence, etc.

In the past year we have shown that our new potential with composite absorption²⁹, derived from the 41.23 data for $^{16}\text{O} + ^{28}\text{Si}$ provides better fits to the elastic scattering than our previous potential over a wide range of incident energies. The article on the elastic scattering for this system which is being readied for publication contains all the details. In brief, the real part of this potential is of W-S shape, as used previously³⁰. The imaginary part is of composite shape with a deep W-S interior and a shallow absorptive peak in the surface²⁹. The parameters of this potential are:

$$\begin{aligned} V_r(\text{MeV}) &= 22.10 + 0.453 (E_{\text{lab}} - 45.0) & r_r &= 1.323 \text{ fm}, a_r = 0.485 \text{ fm} \\ W_v(\text{MeV}) &= 2V_r & r_i &= 0.890 \text{ fm}, a_i = 0.485 \text{ fm} \\ W_d(\text{MeV}) &= 0.696 \exp(0.658 E_{\text{lab}}) & r_d &= 1.296 \text{ fm}, a_d = 0.210 \text{ fm to } 0.310 \text{ fm} \\ C_r &= -0.2081 \exp(-0.0631 E_{\text{lab}}), & C_i &= 0, r_c = 1.00 \text{ fm} \end{aligned}$$

The improvements brought by this form, compared to the previously used shallow absorptive potential of simple W-S form, are many fold. First, the values of χ^2/N at the forward angles are improved over the whole energy interval in question; second, the calculated cross sections at the intermediate angles $90^\circ < \theta_{\text{cm}} < 135^\circ$ are now in much better agreement with the data, and third, the predicted backward rise is now much closer to the $[P_\ell(\cos \theta)]^2$ inferred from the data.

The significance of the new composite form of $W(r)$ in the optical potential goes beyond the listed improvements in the fits and the fact that the region of its application is extended by 3-5 MeV on either side of the previously covered energy interval, $45 < E(\text{lab}) < 63$ MeV. We have also found strong evidence that the peak in $W(r)$ in the surface and probably part of the interior absorption are due to the coupling to the low-lying collective states in ^{28}Si . Coupled channels calculations were done using the (present) optical potential with reduced real strength and only the interior absorption. Assumed was two-way coupling between the 2^+ , 1.78 MeV, excited state and the ground state, and a deformation parameter $\beta_2 = -0.32$. From the radial wave functions obtained from these calculations we selected seven, centered around the grazing partial wave and calculated for each the changes in the optical potential necessary if it were to be used in optical model calculations without coupling. These changes are strongly L -dependent and we have not yet arrived at definite systematic rules on how to incorporate these changes in an L -independent potential. A systematic study of the coupled-channels approach for this system, and of the appropriate ways of adding the contributions to absorption for individual partial waves, should tell us how much of the absorption is due to coupling to the 2^+ excited state.

We have also studied the problem of the ambiguity between the parity dependence and the absorption. Table IV-1 shows for the angular distribution at $E(\text{lab}) = 41.23$ values of χ^2/N using a grid for W_d (strength of surface absorption) and C_p (coefficient of parity dependence). The geometries of the interior and the surface absorption were searched until convergence. This approach focuses on the absorption in the "pocket" since the contribution to the cross sections at the large angles comes from the "pocket", and the parity dependence affects only the large angles. At 41.23 MeV the

ambiguity has not been resolved yet, possibly due to the uncertainties in the data. (We have found that by introducing a "bump" into the real potential at this energy we can reduce χ^2/N to ~ 3.5 . The fit is, however, of the same quality as those with $\chi^2/N \sim 7$ due to small changes in the fit at the forward angles where the assigned errors are small and influence strongly the average χ^2 .) All the fits in Table I for $E(\text{lab}) = 41.23$ MeV with $\chi^2/N < 8$ are equivalent.

In order to gain insight into the details of elastic scattering generated by our new potential we have obtained the wave functions for the partial waves around ℓ_{gr} at $E(\text{lab}) = 55.0$ MeV. Figure 10 shows the moduli $|R_\ell(r)|$ of the radial part of the wave function for each partial wave.

It is readily apparent that we can associate the large peaks at radii between 8 and 10 fm with the combined effect of the Coulomb and centrifugal barriers. The smaller peaks located at radii between 6 and 7 fm, apparently are due to the presence of the "pocket" in the total real potential which is centered at ~ 7 fm. The barrier top is at ~ 8.2 fm. At $E_{\text{lab}} = 55$ MeV ($E_{\text{CM}} = 35.0$ MeV) the relatively weak peak for $\ell = 25$ is due to "tunneling" since the total potential for $\ell \geq 25$ exceeds E_{CM} at the barrier radius (Fig. 11). The peaks for $\ell \leq 24$ can be correlated with the dispersive resonances seen in the phase shifts. The peaks for partial waves with increasingly lower angular momenta become progressively weaker because of increased absorption in the interior. The high sensitivity of the χ^2 at large angles to small variations in $W(r)$ in the region of the pocket makes it quite apparent that the large angle cross sections are mainly due to scattering from "inside" the pocket (see ref. 39).

Table IV.1. Ambiguity between Parity Dependence and Surface Absorption in the Elastic Scattering of ^{16}O from ^{28}Si at 41.23 MeV. Values of χ^2/N are tabulated for fits to the angular distribution using a constant real potential and a constant strength for the absorption in the interior. Geometries of the absorption in the interior and in the surface were varied until the search converged.

$E(\text{lab}) = 41.23 \text{ MeV}$

C_r $W_d(\text{MeV})$	-0.0050	-0.0100	-0.0155	-0.0200	-0.0250
0.350	95.0	73.2	21.9	12.4	35.7
0.700	26.6	14.3	6.5	5.8	7.2
1.050	14.5	8.6	6.1	7.4	9.9
1.400	12.3	8.1	7.0	9.4	12.3
1.750	11.8	8.5	8.6	11.5	14.9
2.100	12.8	9.6	10.3	13.3	14.6
2.450	13.8	11.1	11.8	14.2	14.7

Fig. 10. Moduli of radial wave functions $|R_\ell(r)|$.

We will now discuss a property of the surface-transparent potentials that may be used as a guide in estimating the real well depth. In several studies (ref. 29-35) of elastic scattering of 40-60 MeV ^{16}O on eight targets ranging from ^{16}O to ^{40}Ca it was found that close fits to the data could be obtained only by use of surface transparent potentials. The real and imaginary strengths of these potentials generally increase with energy. Specifically the real well depth increases linearly with energy in this energy range and is deep enough to generate a "pocket" in the total potential $V_{\text{tot}}(r, \ell)$ at least for partial waves around and below the grazing partial wave (Fig. 11), where

$$V_{\text{tot}}(r, \ell) = -V_0 f(r) + \frac{Z_1 Z_2 e^2}{r} + \frac{\hbar^2}{2\mu r^2} \ell(\ell + 1). \quad \text{Eq. IV.1.1.}$$

The pocket causes a discontinuity (as a function of ℓ) in the distance of closest approach (e.g. at $\ell \approx 24$ for $^{16}\text{O} + ^{28}\text{Si}$ at 35 MeV (c.m.)). Assuming analytic continuity for ℓ we can define an angular momentum ℓ_c by the condition that $E_{\text{c.m.}}$ is tangential to V_{tot} at the barrier top radius $r_b = \tilde{r}_b (A_1^{1/3} + A_2^{1/2})$. This condition can be expressed by two equations

$$\left. \frac{dV_{\text{tot}}}{dr} \right|_{r_b, \ell_c} = 0 \quad \text{and} \quad V_{\text{tot}}(r_b, \ell_c) = E_{\text{c.m.}} \quad \text{Eq. IV.1.2.}$$

We find that ℓ_c is very close to the grazing angular momentum ℓ_{gr} derived from the quarter-point angle ($\ell_{\text{gr}} = \eta \cot \frac{\theta_{1/4}}{2}$) and also to the critical angular momentum ℓ_{cr} from the S-matrix elements, ($|S_{\ell_{\text{cr}}}|^2 = 0.5$).

Since the reduced radius, $\tilde{r}_b$, appears to be quite independent of target mass and incident energy eq. IV.1.2 may be used as a guide to estimate the real well depth simply from ℓ_{gr} (derived from $\theta_{1/4}$) provided that $\ell_{\text{gr}} \approx \ell_c$. We have used this procedure for the analysis of $^{16}\text{O} + ^{40}\text{Ca}$ data with encouraging results.

$^{28}\text{Si} + ^{16}\text{O}$, el. scatt., $E(\text{lab}) = 55.0 \text{ MeV}$

26.630, 1.323, 0.485, -0.0020
3.877, 1.350, 0.300, "
1.000

Fig. 11. Absorption coefficient $\eta_\ell = 1 - |S_\ell|^2$ as a function of ℓ (left) and the total potential energy $V_{\text{tot}}(r, \ell)$ for $\ell = 23, 24$, and 25 (right).

2. The $^{16}\text{O} + ^{40}\text{Ca}$ Potential Between 37 and 65 MeV

The data of Kubono et al (ref. 35) for the elastic scattering of ^{16}O from ^{40}Ca consist of one complete angular distribution at $E(\text{lab}) = 50.0$ MeV and a 180° excitation function taken between $E(\text{lab}) = 37.29$ MeV and 70.25 MeV. Kubono's fit to the angular distribution (Fig. 12) is very good up to $\theta_{\text{cm}} \sim 120^\circ$ but contains one peak more than the data at larger angles. Thus the fit is out of phase with the data at some angles. No fit to the 180° excitation function was presented in ref. 35. Angular distributions measured over limited ranges of angles exist at the following energies: $E(\text{lab}) = 38.0, 40.0$ and 42.0 MeV (ref. 36), at $E(\text{lab}) = 40.0$ MeV (ref. 37), at $E(\text{lab}) = 55.6$ and 60.0 MeV (ref. 38), and at $E(\text{lab}) = 74.4$ (ref. 40).

We have obtained fits to the 50.0 MeV angular distribution using surface-transparent and parity-dependent optical potentials with real parts of simple and composite geometries and imaginary parts of composite geometry. A representative fit is shown in Fig. 13. These optical potentials employ parity dependence in their real and imaginary parts. The strength of the parity dependence is only $1/4$ to $1/3$ of what was used with the potential with composite $W(r)$ for $^{16}\text{O} + ^{28}\text{Si}$ at $E(\text{lab}) = 50.0$ MeV. The fit shown in Fig. 13 is perfect at large angles but not quite adequate at the forward angles. We hope that the use of a deeper real part and especially the use of a deeper interior absorption, like in the case of $^{16}\text{O} + ^{28}\text{Si}$, will provide a better fit. Yet, by using the geometry parameters

$$\begin{aligned} r_r &= 1.431 \text{ fm}, & a_r &= 0.350 \text{ fm}, & r_{\text{coul}} &= 1.200 \text{ fm} \\ r_i &= 1.427 \text{ fm}, & a_i &= 0.161 \text{ fm}, & r_d &= 1.731 \text{ fm}, & a_d &= 0.080 \text{ fm}, \end{aligned}$$

Fig. 12. Data and fit of Kubono, et al. (ref. 35).

Fig. 13. Fit to data of ref. 35 from this work.

and the energy dependence of the real and interior imaginary strengths V_r and W_v as shown in Fig. 14, constant absorption in the surface $W_d = 0.136$ MeV, and constant parity dependence $C_r = C_i = -0.0023$, we obtained a good fit over a substantial portion of the $(180 \pm 5.7)^\circ$ excitation function (Fig. 15). The dashed line in Fig. 14 is a prediction for $V_o(E_{cm})$ using the method (Eqs. IV.1.1) outlined in the previous section.

Fig. 14. Energy dependence of real and imaginary depths used in fits to the $^{160}\text{Pb} + ^{40}\text{Ca}$ 180° excitation function shown in Fig. 15.

Fig. 15. $^{16}\text{O} + ^{40}\text{Ca}$ excitation function (ref. 35) and fits from this work.

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V. Publications, Abstracts, Invited Talks

A. Publications

D. B. Holtkamp, W. J. Braithwaite, W. Cottingame, S. J. Greene, R. J. Joseph, C. Fred Moore, C. L. Morris, J. Piffaretti, E. R. Siciliano, H. A. Thiessen, and D. Dehnhard, "Isospin Mixing of 4^- Particle-Hole States in 160 ," Phys. Rev. Letters 45, 420-423 (1980).

W. B. Cottingame, and D. B. Holtkamp, "Energy Dependence of Pion Elastic Scattering from Nuclei Across the (3,3) Resonance," Phys. Rev. Letters, published Phys. Rev. Letters 45, 1828 (1980).

G. R. Burleson, G. S. Blanpied, G. H. Daw, A. J. Viescas, C. L. Morris, H. A. Thiessen, S. J. Groono, W. J. Braithwaite, W. Cottingame, D. B. Holtkamp, C. Fred Moore, and I. B. Moore, "Isospin Quintets in the $1p$ and $s-d$ Shells," Phys. Rev. C, 22, 1180-1183 (1980).

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B. Papers in press or submitted for publication

Christopher L. Morris, Kenneth G. Boyer, C. Fred Moore, Carol J. Harvey, K. J. Kallianpur, Ingrid B. Moore, Peter A. Seidl, Susan J. Seestrom-Morris, D. B. Holtkamp, Steven J. Greene, and William B. Cottingame, "Pion Inelastic Scattering to Low-Lying States in ^{12}C and ^{40}Ca ," Phys. Rev. C., to be published.

C. L. Morris, R. L. Boudrie, J. Piffaretti, W. B. Cottingame, W. J. Braithwaite, S. J. Greene, C. J. Harvey, C. Fred Moore, D. B. Holtkamp, S. J. Tripp, "Measurements of Isospin Mixing Between the 1^+ Doublet in ^{12}C Using Pion Inelastic Scattering," submitted for publ..

S. J. Seestrom-Morris, D. Dehnhard, D. B. Holtkamp, and C. L. Morris, "Identification of $\Delta S=1$ Transitions by Measurement of Pion Inelastic Excitation Functions," submitted for publ..

C. Papers in progress

D. B. Holtkamp, S. J. Seestrom-Morris, S. Chakravarti, D. Dehnhard, H. W. Baer, C. L. Morris, S. J. Greene, and C. J. Harvey, "Strong Cancellations of Neutron and Proton Transition Amplitudes in Pion Inelastic Scattering from ^{14}C ."

S. J. Seestrom-Morris, D. Dehnhard, et al., "Structure of ^{13}C Studied

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D. Contributions to Conferences and Workshops

S. J. Tripp, D. Dehnhard, M. A. Franey, G. S. Kyle, C. L. Morris, R. L. Boudrie, J. Piffaretti, and H. A. Thiessen, "Energy Dependence of Inelastic Pion Scattering from ^{13}C ," Proceedings of the LAMPF Workshop on Nuclear Structure with Intermediate Energy Probes, Los Alamos, New Mexico, LASL Report no. LA-8303-C, p. 328 (1980).

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V. Shkolnik, M. A. Franey, and D. Dehnhard, "A Composite Absorptive Potential for $^{16}\text{O} + ^{28}\text{Si}$ Elastic Scattering", Proceedings of the International Conference on Nuclear Physics, Berkeley, California 1980, page 588.

E. Abstracts

D. B. Holtkamp, C. L. Morris, W. B. Cottingame, S. J. Greene, W. J. Braithwaite, C. J. Harvey, C. F. Moore, I. B. Moore, P. A. Seidl, "A Study of the 1^+ States of ^{12}C with Pion Inelastic Scattering: Angular Distributions and Excitation Function," Bull. Am. Phys. Soc. 25, 730-731 (1980).

C. Fred Moore, W. J. Braithwaite, C. J. Harvey, K. Kallianpur, I. B. Moore, P. A. Seidl, D. B. Holtkamp, W. B. Cottingame, S. J. Greene, C. L. Morris, "A Comparison of Inelastic Pion Scattering from Self Conjugate Nuclei ^{40}Ca and ^{12}C ," Bull. Am. Phys. Soc. 25, 731 (1980).

R. L. Boudrie, J. F. Amann, G. C. Idzorek, S. J. Seestrom-Morris, D. B. Holtkamp, M. A. Franey, D. Dehnhard, C. Goulding, "Scattering of 547 MeV Polarized Protons from ^{13}C ," Bull. Am. Phys. Soc., to be published.

S. J. Seestrom-Morris, D. Dehnhard, M. A. Franey, G. S. Kyle, C. L. Morris, R. L. Boudrie, J. Piffaretti, and H. A. Thiessen, "DWIA Analysis of Elastic and Inelastic Scattering of Pions from ^{13}C ," Bull. Am. Phys. Soc., to be published.

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F. Invited Talks

D. Dehnhard
Nuclear Seminar at the University of Pennsylvania.
Invited talk on "Unnatural Parity Excitations in Intermediate Energy Pion and Proton Scattering," given at the Minneapolis Meeting of the Division of Nuclear Physics, Oct. 9-11, 1980, Bull. Am. Phys. Soc. 25 (1980) 732, paper CA3.

G. Advanced Degree Granted

Susan J. Seestrom-Morris, Ph.D. March '81.
Thesis title: "The Structure of ^{13}C Studied by Pion Scattering Near the (3,3) Resonance."

VI. Distribution of Effort of Principal Investigator

1979-80	Acad. Year	(June 1-15, 1980)	45%
1980	Summer	(July 1 - Sept. 15, 1980)	100%
1980-81	Acad. Year	(Sept. 16 - Dec. 15, 1980)	90%
1980-81	Acad. Year	(Dec. 16 - present)	50%
Expected contribution from present to May 31			50%