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"Research in Experimental Nuclear Physics"

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A Contract Between
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31 December 1977

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I. INTRODUCTION

This report covers the first full year of medium energy physics research activity of the University of Texas at Austin supported by the U. S. Research and Development Administration through contract EY-76-S-05-5224.

During contract period 1977-1978 several experiments ran to completion and several were initiated. The research effort has mainly involved experiments using the High Resolution Spectrometer (HRS) and the Energetic Pion Channel and Spectrometer (EPICS) at the Los Alamos Clinton P. Anderson Meson Physics Facility. Highlights of this research are included in this report.

The University of Texas has had one of its faculty members on site at LAMPF during each of the spring and fall semesters, and the three of us on site during the summer period, during this contract year. There are ten graduate students associated with the program, five of which were on site at LAMPF during this report period. One technical support person has also been on site during this period.

The research program has progressed fairly well. Data taken at LAMPF has been analyzed using the PDP11/45 computer in Austin. Equipment for experiments at LAMPF has continued to be constructed in Austin, as well as some equipment for the basic facility. The graduate students associated with the University of Texas effort are taking courses designed to aid their future research efforts at LAMPF. Those graduate students in residence at LAMPF have been involved in specific experiments in which they have a fair share of the primary responsibility for the completion of the work.

Two University of Texas students have already received their Ph.D. degrees for work done at LAMPF in medium energy physics. Dr. Joseph Bolger is presently working at SIN in Switzerland, and Dr. Gary Blanpied is presently working at LAMPF with the New Mexico State University group.

The work cited in this report of course is the collaborative effort of many groups associated with research at LAMPF. Collaboration with LASL, BNL, UCLA, Northwestern, Colorado, Oregon, Virginia, Oregon State and Rutgers is acknowledged.

~~II.~~ RESEARCH WITH THE HIGH RESOLUTION SPECTROMETER AT LAMPF

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Proton elastic differential cross sections at medium energies are known to be sensitive to the nuclear matter density distributions.$^{1)}$ However, the accuracy to which details of the densities may be extracted from the data depends upon the sensitivity of the analysis to the density distributions, as well as upon other uncertainties and approximations which are associated with the analysis.$^{1-2)}$ In the past, various attempts, using either the multiple scattering formalism$^{3)}$ (Glauber theory) or the optical model with a microscopic potential$^{4)}$ (Kerman-McManus-Thaler, KMT) have been made to study the neutron density distributions in a variety of nuclei.$^{5-8)}$ However, lack of high quality data extending to large enough momentum transfer (about 4 fm^{-1}), as well as the major uncertainty associated with the analysis$^{1-2)}$ (spin-effects) have limited confidence in the extracted neutron density parameters to the root-mean-square (rms) radii only.$^{1)}$

In has been known for some time that reliable spin-dependent nucleon-nucleon parameters are needed if any attempt is to be made at extracting details of the nuclear density distributions. This is because spin-effects were expected to be large, and preliminary calculations$^{1-2)}$ indicated that spin-effects could affect the elastic angular distributions in much the same way as do density fluctuations near the nuclear surface (roughly, the effects seen in varying the diffuseness). Spin-dependent nucleon-nucleon amplitudes as extracted from pp and pn polarization data would remedy the situation, but unfortunately, experimental data is not yet available from which such amplitudes may be obtained. Another approach to understanding spin-effects is through the proton plus nucleus analyzing power which may be obtained through experiments with polarized proton beams.

In order to systematically study spin-effects in elastic scattering and provide data which test existing theories which incorporate spin-dependent amplitudes, Experiment 311 (Elastic Scattering Survey Using Polarized Protons, G. W. Hoffmann, Spokesman) was done during Cycles 14-18 at LAMPF using the High Resolution Spectrometer (HRS) facility. Over 700 hours of production time was used for the experiment. Differential cross section ($d\sigma/d\Omega$) and analyzing power (A) data was obtained for 800 MeV polarized proton elastic scattering from $^{12,13}C$, $^{40,42,44,48}Ca$, $^{46,48,50}Ti$, $^{58,64}Ni$, ^{90}Zr, $^{116,124}Sn$, ^{54}Fe and ^{208}Pb over the laboratory angular range 3^o - 23^o. Much of the data has already been reduced to semi-final form, and theoretical interpretation has been started.

Considerable care was taken to insure the accuracy of the data. Absolute scattering angle was determined to $\pm$ 0.05^o by making successive data runs with the HRS set at $\pm$ 12^o on several occasions. Also, much of the data taken during one running cycle was retaken during another cycle to insure repeatability. The beam polarization was determined on-line for each run using a four-arm polarimeter upstream of the target which monitored H(p,p)H scattering at 45^o c.m. on both sides of the beam line. A value of 0.48 $\pm$ 0.01 was determined for the analyzing power for H(p,p)H at 45^o c.m. by calibrating the polarimeter using the source quench ratio technique.9) Our result for the H(p,p)H analyzing power also agrees with that determined independently by Willard, et al.10) using the same technique on the EPB channel at LAMPF. Beam polarization during the course of the experiment was typically 87%, and statistical uncertainty in the calculated beam polarization was much less than 1% for each run. During the course of the experiment beam polarization was reversed automatically at the source every three minutes, and runs typically took one hour per target per angle.

Of concern during the experiment was the possibility of changes in beam phase space with polarization reversal, particularly those changes which may be related to a change in beam angle on target. Although we looked for such beam phase space-spin orientation correlations, none were observed at the limit of the beam monitoring equipment which set an upper limit estimate of $\Delta A = \pm 0.01$ for the worst case due to this effect.

Shown in Figs. 1-4 is some of the experimental data obtained, along with the results of preliminary theoretical analyses. The errors shown on the figures are statistical only. For the differential cross sections they are typically less than 2% (smaller than the data points) and for the analyzing powers they are typically 0.01 - 0.02 except for the larger angles. Overall normalization of the differential cross section data was obtained by taking H(p,p) data on a CH target and normalizing to H(p,p) data of Willard, et al.11) These normalization measurements were made during each running cycle, and the absolute normalization of the data is believed reliable to within ± 15%. In the future we expect to renormalize to an accuracy of ± 5% via absolute cross section determination at HRS.

The interesting features of the analyzing power data are that (1) the analyzing powers are always positive (same sign as the pp analyzing power), (2) the oscillatory frequencies are characteristic of the differential cross sections, (3) a general rule appears to be that the minima in the differential cross sections are located midway in angle between the minima and maxima of the analyzing powers, and (4) the envelopes monitonically increase with angle (except ^{12}C near 30°). These features of the data can be qualitatively understood employing a classical description of the scattering process. Fig. 5 shows schematically a cross section of the real spin-orbit potential as seen by the incident nucleon for spin-up (solid line) and spin-down (dashed line) as well as the central imaginary potential which is the same for both spin orientations. The arrows represent the directions of the classical deflections due to the spin-orbit potential as the protons pass different regions of the nucleus (into the page) for the two spin orientations. As seen from the figure, regions 1 and 4 scatter spin-up protons to the left, while regions 6 and 7 scatter spin-down protons to the left. Since, for the spin-up case, the scattering regions are at larger radii than for the spin-down case, the nucleus effectively looks larger for the spin-up protons and the $d\sigma/d\Omega(\sigma\uparrow,\text{left})$ diffractive pattern should be shifted to smaller angles, while the $d\sigma/d\Omega(\sigma\downarrow,\text{left})$ pattern should be shifted to larger angles as compared to the diffractive pattern when the spin-orbit potential is turned off. Also, note from Fig. 5 that because of the imaginary potential, more absorption will occur for the spin-down scattering to the left than for spin-up to the left, so that $d\sigma/d\Omega(\sigma\uparrow,\text{left})$ should be larger than $d\sigma/d\Omega(\sigma\downarrow,\text{left})$. The absorption is large (depth about -60 MeV) so the effect is substantial. The net effect, then, is to reduce the spin-down cross section considerably and shift its diffractive pattern to larger angles as compared to the spin-up case (see Fig. 6 which shows the actual differential cross sections for ^{90}Zr for the two beam spin orientations). Such effects qualitatively explain the behavior of the analyzing powers observed. At lower energies (E about 50 MeV and less) the imaginary potential does not play such an important role, and in this case, the angle shift dominates with the spin-up and spin-down cross sections crossing one another, leading to analyzing powers which oscillate about zero. A simple quantitative approach using the diffractive model also predicts analyzing powers at medium energies which qualitatively resemble the experimental data.

The curves shown in Figs. 1-4 were generated by solving the Schrodinger equation with relativistic kinematics$^{12)}$ and the first-order KMT microscopic optical potential which is derived from nucleon-nucleon scattering amplitudes and the nuclear matter densities. The spin-independent amplitudes (see Table

1 and Fig. 7) were determined from nucleon-nucleon data[13)] taken near 800 MeV. The proton densities were taken from electron scattering results.[14-16)] Both the spin-independent amplitudes and the proton densities were then treated as fixed. The only remaining variables were those of the spin-dependent nucleon-nucleon amplitudes and the neutron density distributions. The form chosen for the spin-dependent amplitudes was[2)]

$$t^s_{pj}\ (q^2) = (\ ik_o\theta_{pj}/4\pi\ )\ (\ q^2/4M^2\ )^{1/2}\ (\ 1 - i\ \alpha_{spj}\ )\ \exp\ (\ -B_{spj}\ q^2\ )$$

for j = p or n and q is the momentum transfer. In this first attempt at understanding spin-effects, the parameters (3-parameter Fermi or 3-parameter Gaussian, plus small corrections for ^{12}C and ^{208}Pb) of the neutron density and the three isospin-averaged spin-dependent nucleon-nucleon parameters were searched to provide simultaneous fits to both the differential cross sections and the analyzing powers. Since there is no fundamental reason to expect the pp and pn spin-dependent amplitudes to be the same, the isospin-averaged spin-dependent parameters were allowed to vary from nucleus to nucleus as N/Z changes. Table 2 gives preliminary values for the neutron density parameters found from the analysis, as well as the isospin-averaged spin-parameters used. Figs. 8-11 show some of the preliminary neutron densities which have been obtained in this way from the experimental data.

Table 3 compares the differences Δr_{np} between the neutron and proton rms radii with results of Hartree-Fock predictions. The agreement is quite encouraging.

We have also determined the effect of the first-order spin-orbit term on the determination of the neutron density. The neutron rms radii determined with $\bar{\theta}_p = 0$ are generally reduced by about 0.03 fm from those found with $\bar{\theta}_p \neq 0$. However, the geometry is found to be more sensitive as can be seen in Fig. 12 which shows the differences in the neutron densities for ^{124}Sn determined with (solid curve) and without (dashed curve) the spin-orbit term. Also shown in Fig. 12 as the dot-dashed curve is the neutron density as found from analysis of the differential cross section data where the spin-dependent parameters were taken as the average of the ^{58}Ni, ^{124}Sn, and ^{208}Pb parameters. This density is identical for r greater than 5 fm to that found by freely searching the spin-parameters, and the two densities differ by at most 2% for r less than 5 fm.. Of course, no claim is being made that such analysis determines the neutron densities to 2% in the nuclear interior. In all cases good fits to the angular distributions were obtained.

Three aspects of the results obtained so far are quite encouraging as to the meaningfulness of this type of work as regards neutron density distributions. The first is the good overall agreement between the preliminary results reported here and those predicted by Hartree-Fock for Δr_{np}. A variety of other experimental works have provided data from which the analysis concluded that Δr_{np} for nuclei with large neutron excesses, e.g., ^{48}Ca and ^{208}Pb, were consistent with zero and in violent disagreement with Hartree-Fock predictions.17) Although taking Hartree-Fock predictions as gospel would mean that taking data in the first place was a waste of time, the systematic general overall agreement of the present results with Hartree-Fock predictions for a variety of nuclei which span the periodic table is significant. The second noteworthy remark is the sensitivity of the calculations to the neutron density distributions. Shown in Fig. 13 is the oscillatory correction needed for the ^{208}Pb neutron density (see Table 2) in order to provide a good fit beyond 20° to the differential cross section as shown in Fig. 1. Fig. 14 shows the results of calculations with and without this correction. The solid curve of Fig. 14 is the one shown in Fig. 1. It is quite encouraging that the calculations are this sensitive to small fluctuations in the densities, although the uniqueness of such a correction must await a more detailed theoretical study in which all known corrections to the theory are made. Thirdly, shown in Fig 15 as the solid curve, is the difference between the ^{124}Sn and ^{116}Sn neutron densities as determined by the present preliminary analysis. Shown as the dotted line is the difference as predicted by Hartree-Fock. The agreement is remarkable and indicates that medium energy elastic scattering data may indeed be invaluable for studying the details of neutron density distributions in nuclei, particularly neutron density differences for isotopic sequences.

Some of the data for elastic and inelastic 800 MeV proton scattering on ^{12,13}C is shown in Figs. 16-19 together with the results of theoretical analysis. The curves shown in Fig. 17 are results of distorted wave Born approximation (DWBA) calculations. The top three curves were generated using a collective form factor for the transition matrix. Since this form factor is related to the derivative of the matter distribution, a new constraint is added to the determination of the neutron density distribution of ^{12}C not present with analysis of the elastic scattering data only (Fig. 16). The bottom two curves (7.6, 0+) in Fig. 17 were generated using particle-hole form factors (solid, 2p-2h; dashed, 1p-1h) and suggest the possible validity of such calculations for determining the microscopic description of such nuclear states. For the case of the 7.6, 0+ state, the DWBA calculations with collective form factors are out of phase with the data. The 14.08, 4+ state is not even qualitatively reproduced by the calculation, indicating a reaction mechanism other than pure single step.

The curves shown in Fig. 18 are again DWBA calculations using collective form factors with assumed j and ℓ transfers. The state identified as 11.9, 7/2+ is tentatively a new assignment.

In Fig. 19 are the results of coupled-channel calculations for the 0+, 2+, 4+ data shown in Fig. 17. In this case the data is very nicely reproduced (as compared to the DWBA fits shown in Fig. 17) and indicates the importance of 2-step reactions at medium energies. It is interesting that the 14.08, 4+ state appears to be populated almost entirely by the 2-step process.

The ^{12,13}C inelastic data require the introduction of new dimensions into the methods of theoretical analyses needed at medium energies. Reaction mechanisms, nuclear densities, and the derivatives of the densities, all come into play in such analyses as discussed here.

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Table 1: Spin-independent nucleon-nucleon parmaters which were used for the preliminary calculations discussed. The parameterization is

$$t^{o}_{pj}(q^2) = (ik_o\sigma^T_{pj}/4\pi)\ (1 - i\alpha_{pj})\ \exp(-B_{pj}q^2) \text{ for } j = p \text{ or } n.$$

j	$\sigma_{pj}(fm^2)$	α_{pj}	$B_{pj}(fm^2)$
j=p	4.73	0.056	0.090
j=n	3.80	-0.20	0.012

Table 2: 3-parameter Fermi neutron density distributions extracted from the data and the isospin-averaged spin dependent nucleon-nucleon parameters.

Nucleus	w	R	z	$\overline{\theta}_s$	$\overline{\alpha}_s$	$\overline{B}_s$
^{12}C	-.01	2.27	.43	15.0	.31	.05
^{58}Ni	-.11	3.97	.59	15.0	.46	.10
^{90}Zr	-.22	4.82	.69	12.2	.52	.09
^{116}Sn	0	5.39	.59	12.4	.48	.12
^{124}Sn	0	5.59	.58	10.0	.58	.15
^{208}Pb	.34	6.15	3.17	10.0	.57	.11

Table 3: Comparison of Δr_{np} (neutron-proton rms radii differences) with Hartree-Fock.

Nucleus	Δr_{np}(experiment)	Δr_{np}(Hartree-Fock)
^{12}C	0 fm	0 fm
^{58}Ni	0	0
^{90}Zr	.14	.07-.12
^{116}Sn	.10	.14
^{124}Sn	.22	.21
^{208}Pb	.18	.20-.23

Fig. 1

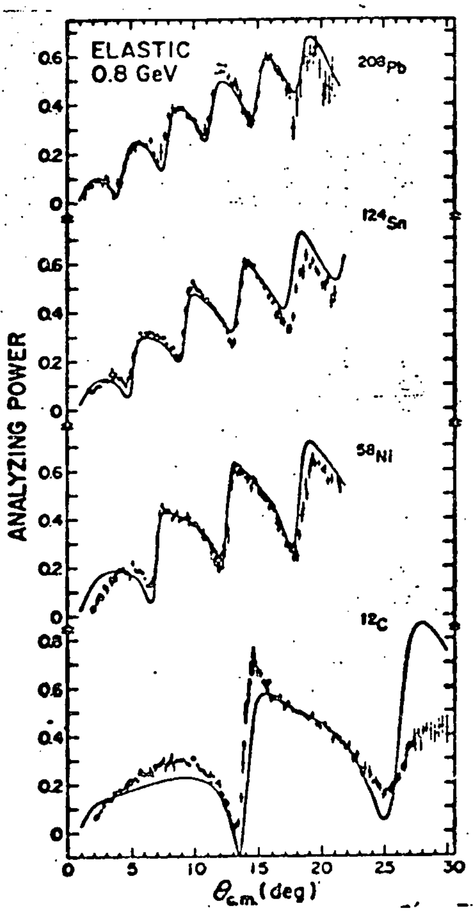
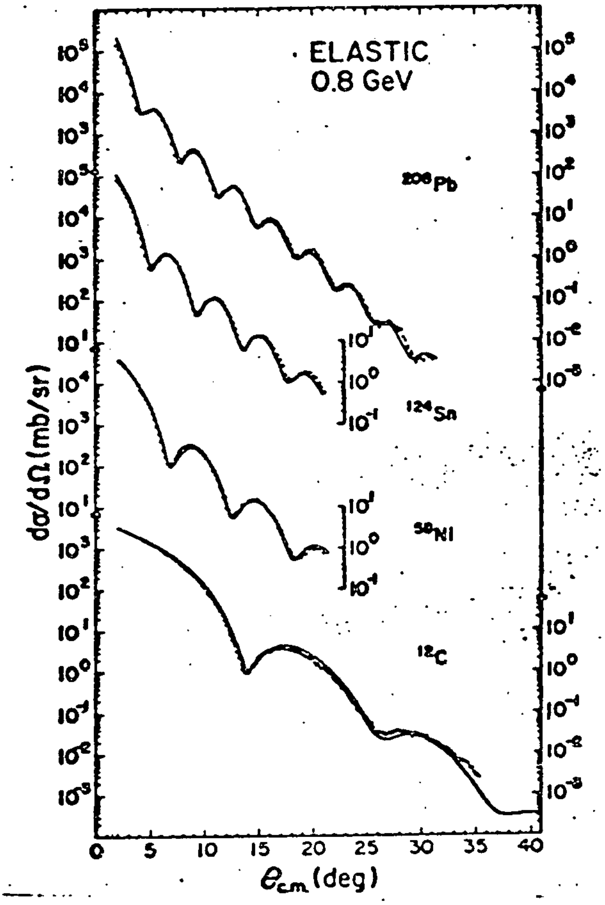


Fig. 2



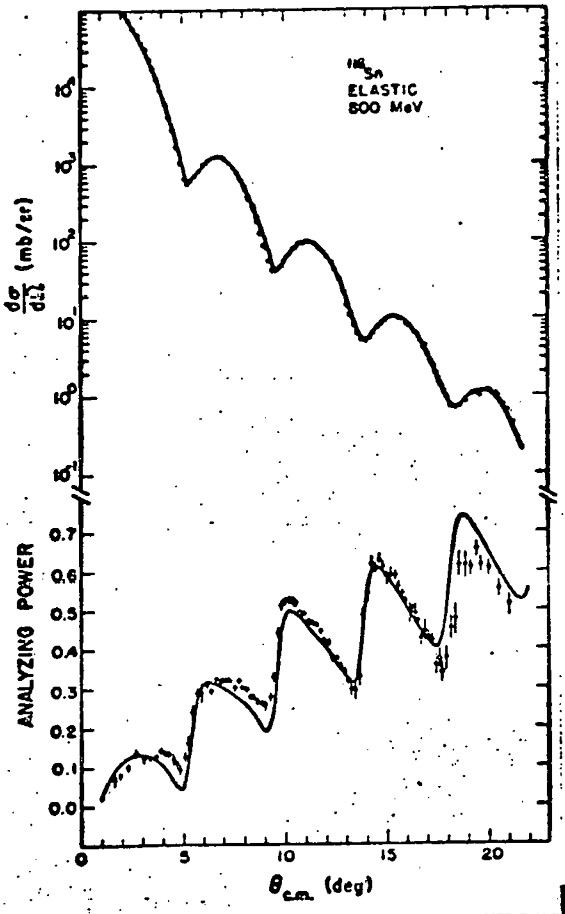


Fig. 3

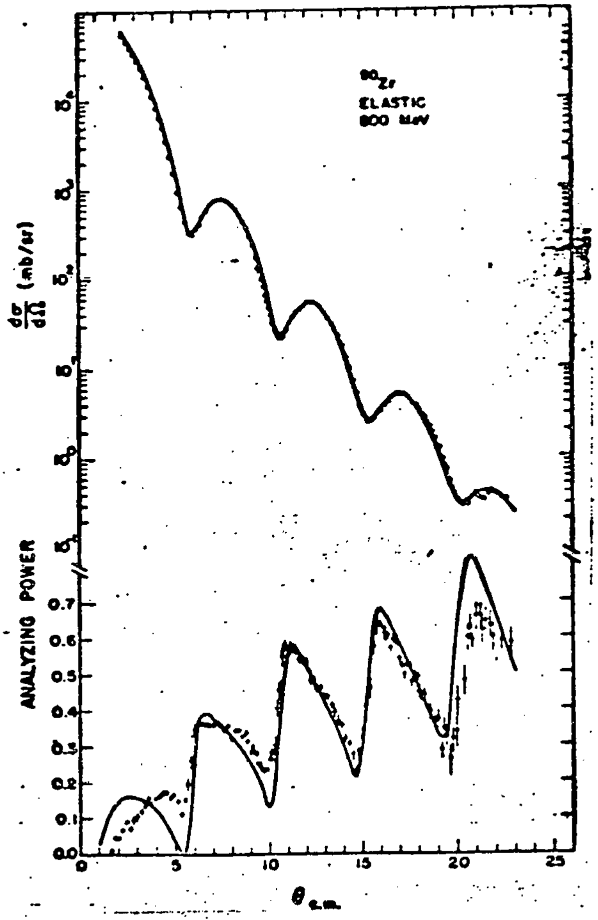


Fig. 4

Fig. 5

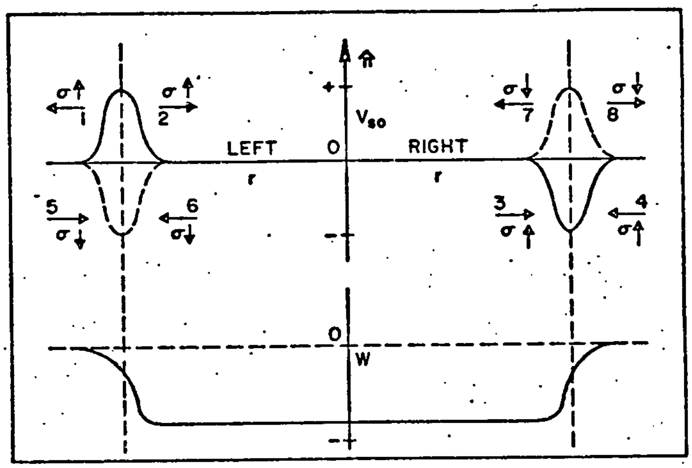
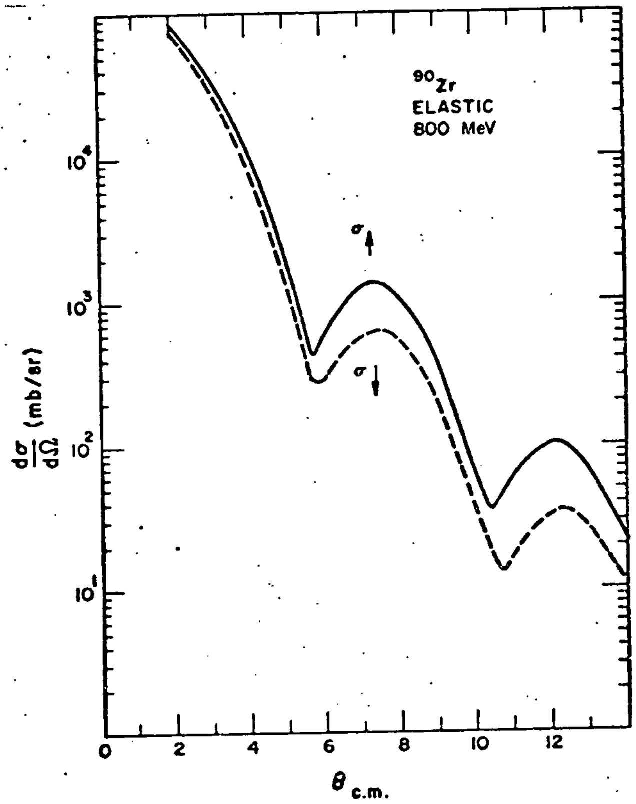


Fig. 6



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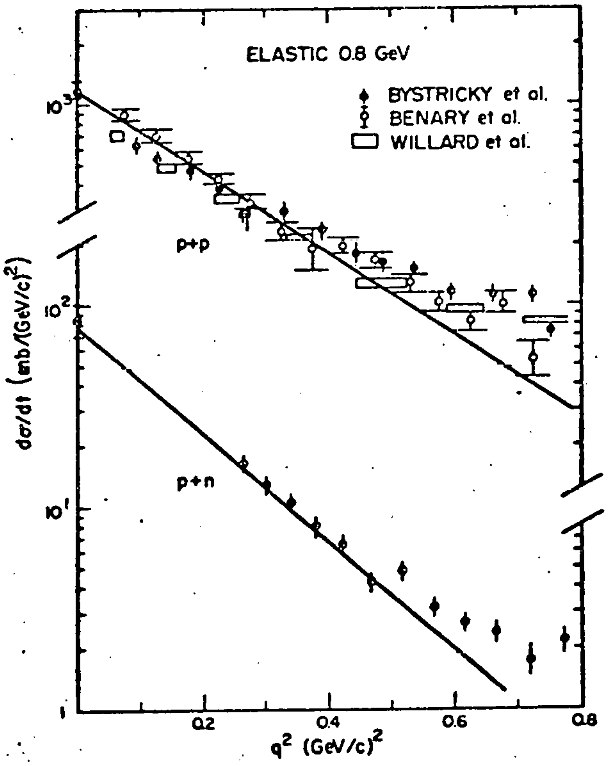

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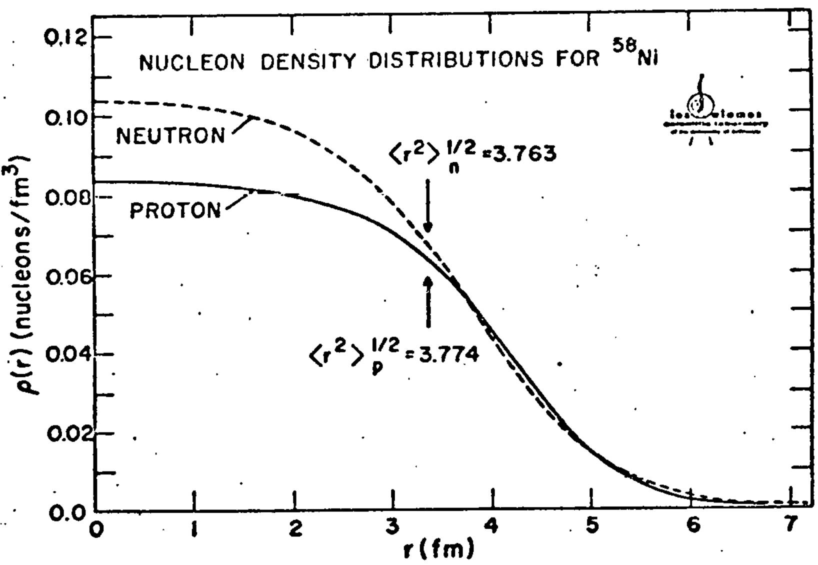

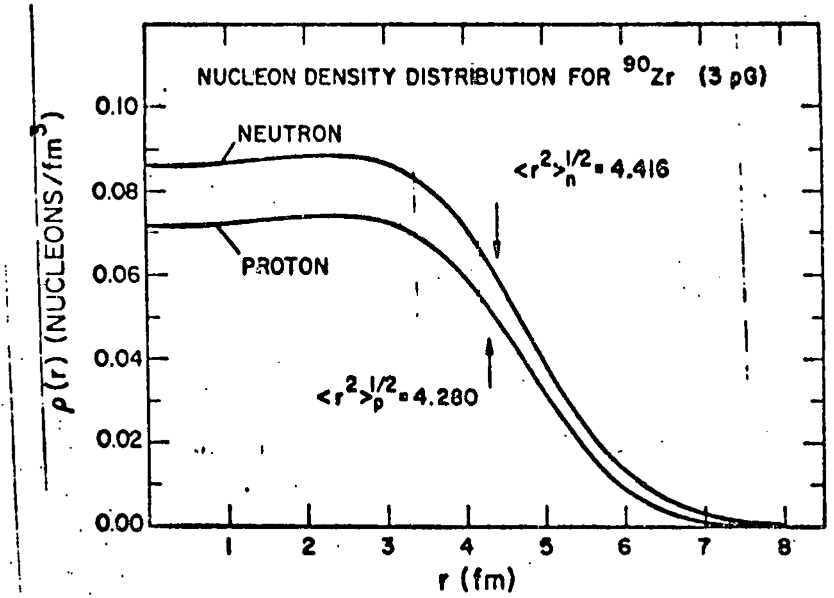

Fig. 9

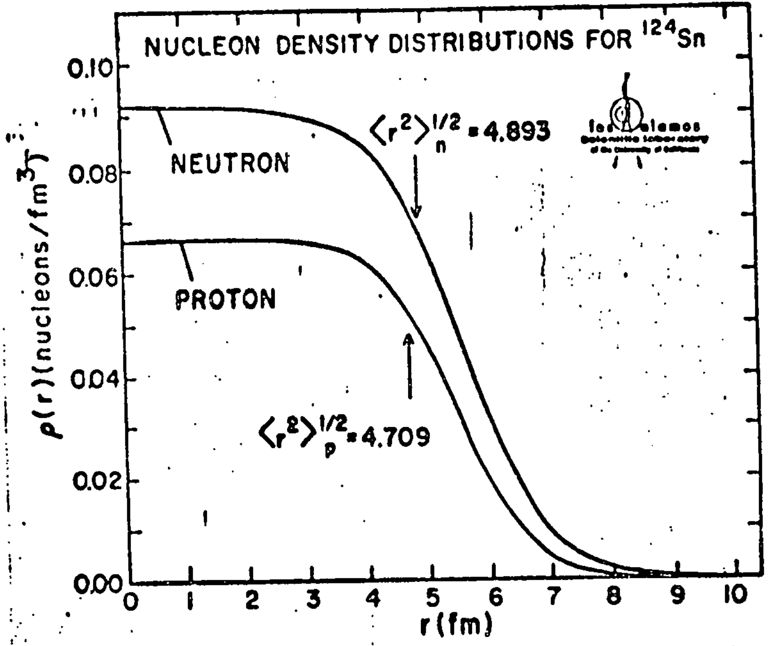

Fig. 10

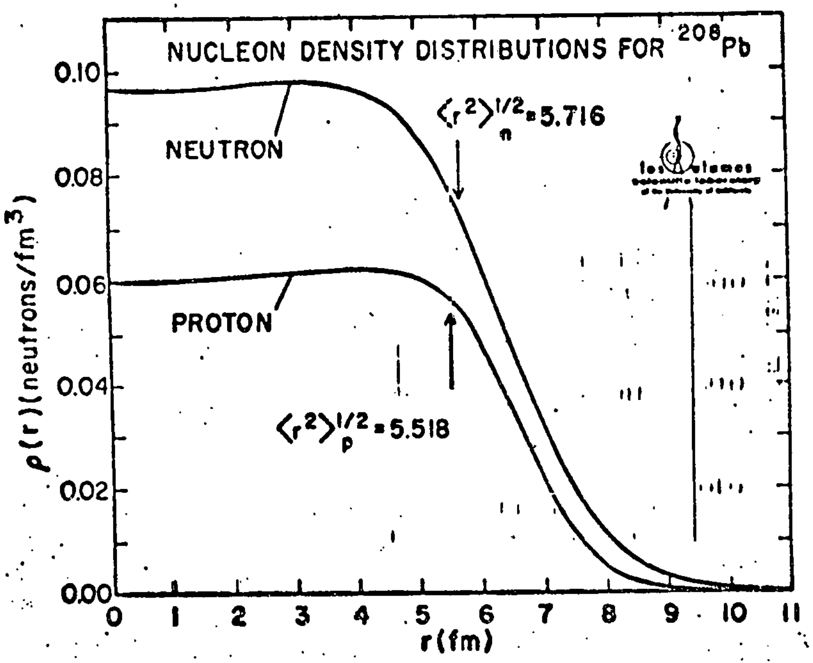

Fig. 11

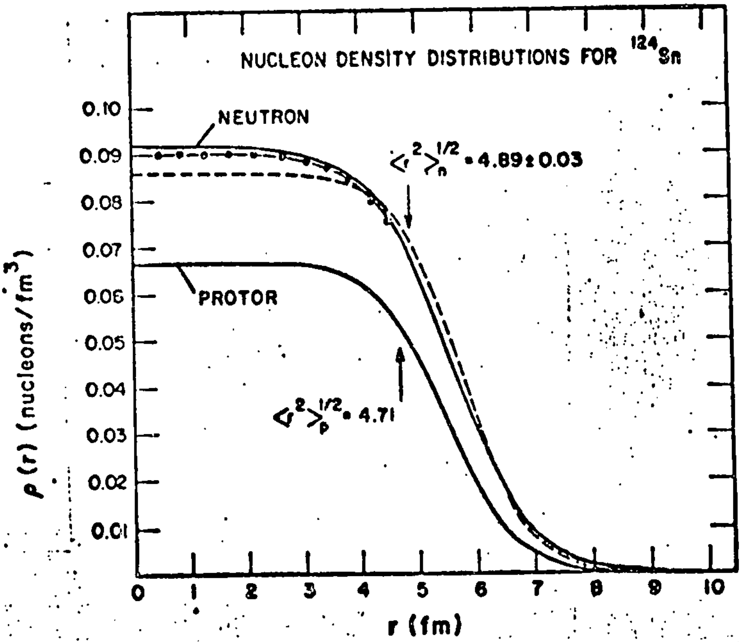

Fig. 12

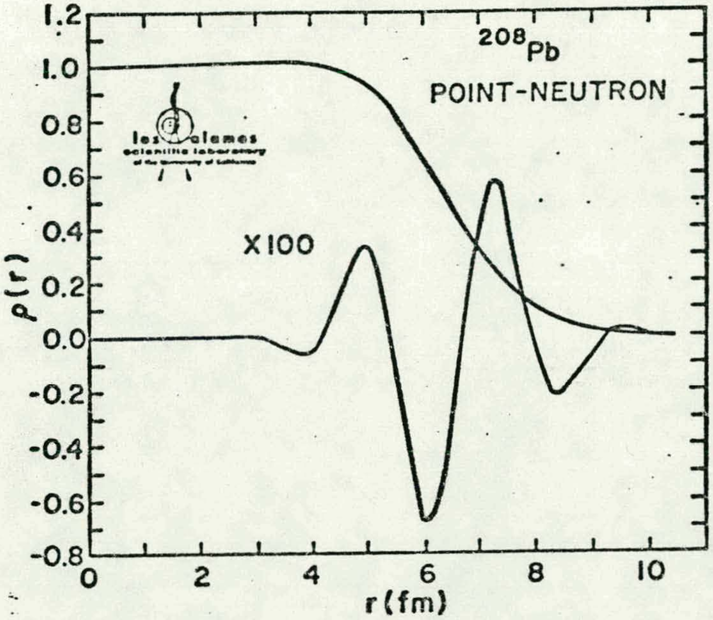

Fig. 13

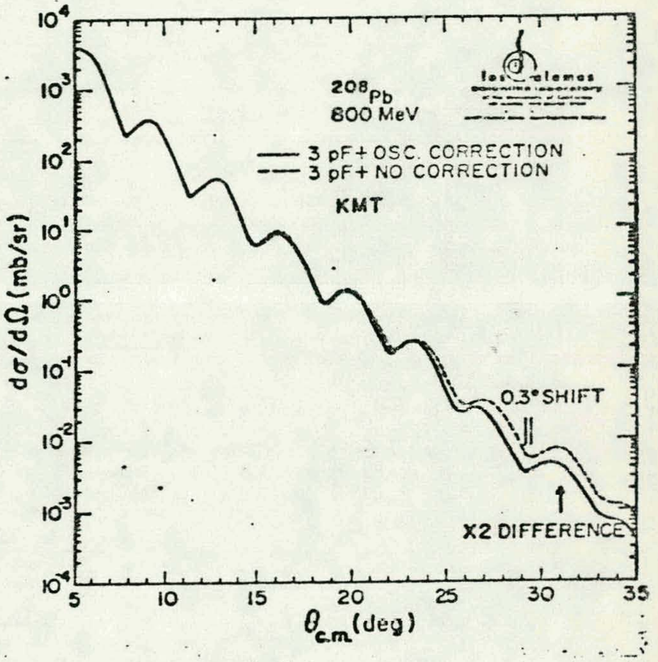

Fig. 14

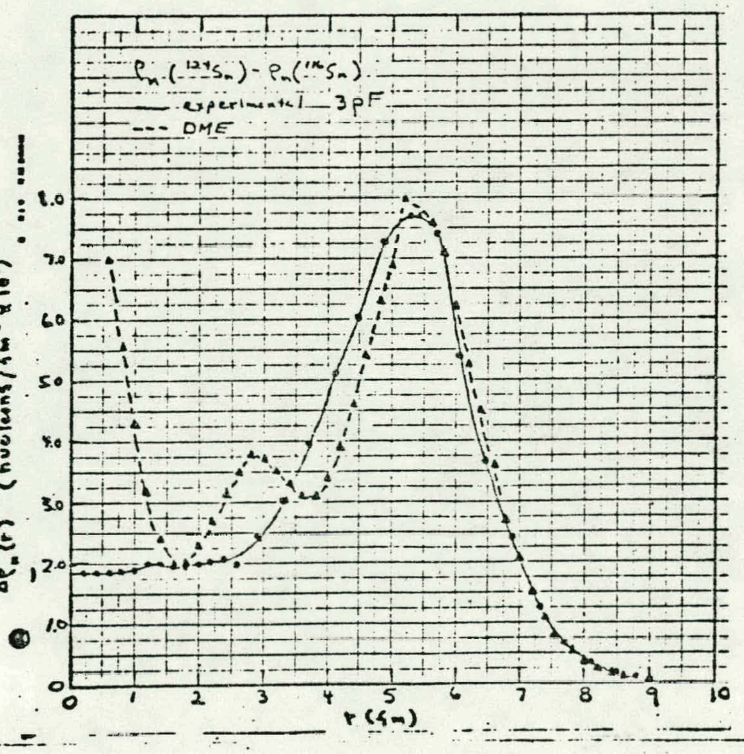

Fig. 15

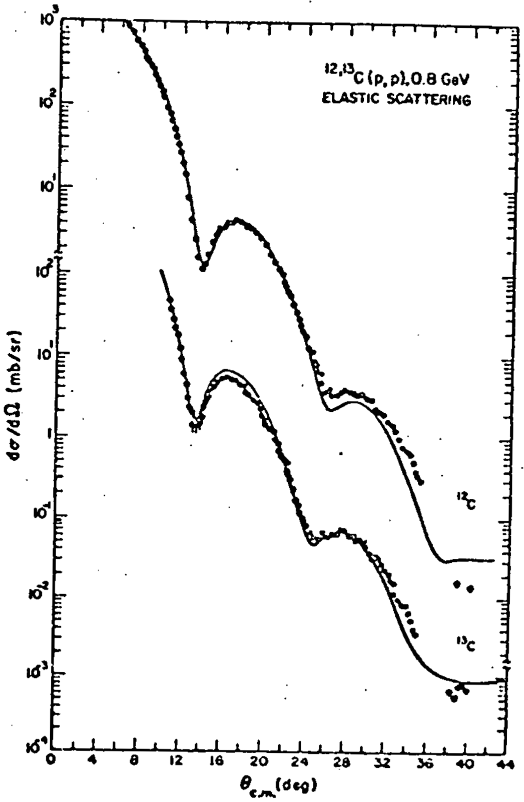

Fig.16

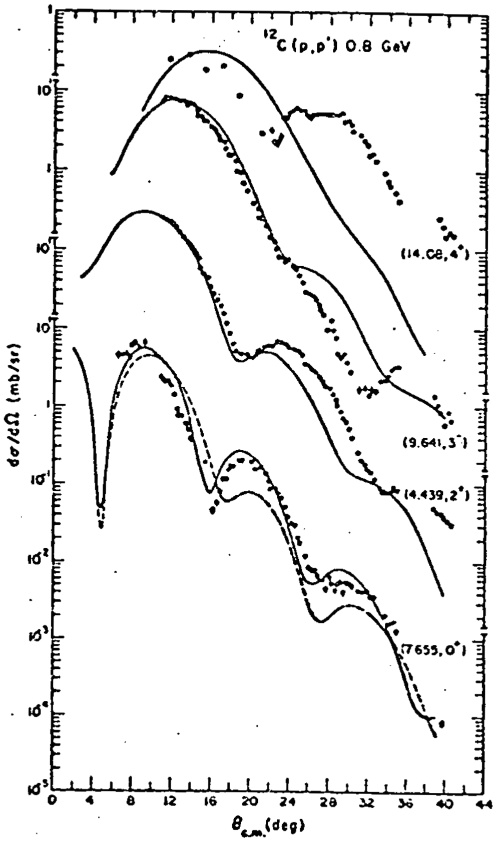

Fig.17

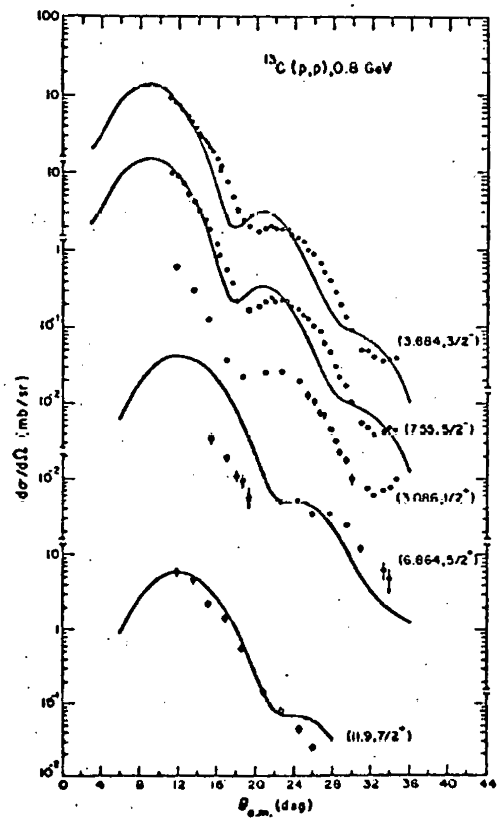

Fig.18

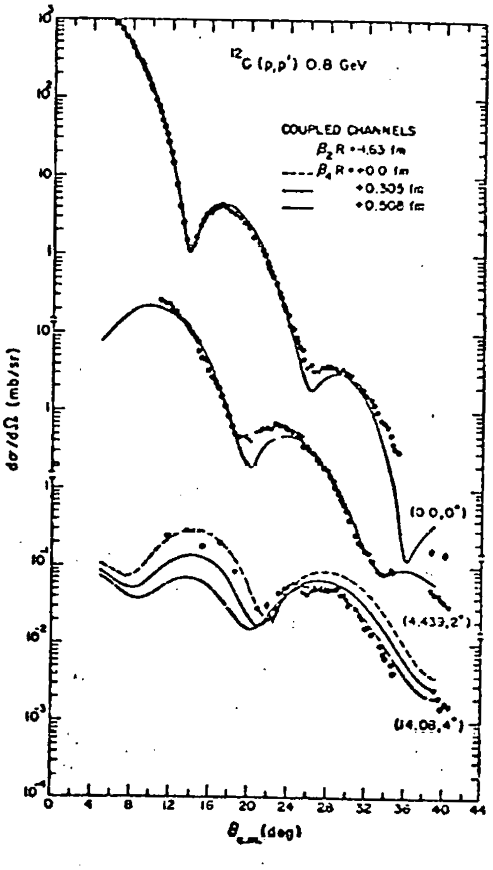

Fig.19

III. RESEARCH WITH THE ENERGETIC PION CHANNEL AND SPECTROMETER

During the past year we have carried out several nucleon-removal experiments using π^+ and π^- to measure the selectivity $R = \sigma(\pi^-)/\sigma(\pi^+)$ for neutron removal and $R = \sigma(\pi^+)/\sigma(\pi^-)$ for proton removal. These experiments were carried out as part of the Los Alamos PAC approved Experiment #265 with the help of collaborators from the University of Colorado and the Los Alamos Scientific Laboratory. Since most of our results are available in the published literature we are not including any figures from this work in the summary writeup of the next section. In addition to measuring pion charge-species selectivity in nucleon-removal, we have begun similar measurements using pion inelastic scattering.

A. Nucleon Removal by Pions

Total cross sections for nucleon removal by $\pi^\pm$, populating individual final states in the residual nuclei, were measured by detecting the de-excitation gamma rays from states not troubled by cascade gamma-ray feeding. The experimental method is outlined in a recent paper.[1]

A selectivity of only R = 3 is expected from free pion-nucleon results using a simple impulse approximation, when the residual nuclei are studied in the nucleon removal experiments.

In our first effort we measured $\pi^\pm + {}^7\mathrm{Li} \rightarrow \pi^\pm + n + {}^6\mathrm{Li}^*$(3.56 MeV, T=1) and only found an experimental value of about R = 2. This work has been published[1] in Physical Review Letters under the title "A Comparison of Neutron Removal from ^{7}Li with Free Pion Nucleon Results." An even smaller enhancement was seen for $\pi^\pm + {}^9\mathrm{Be} \rightarrow \pi^\pm + p + {}^8\mathrm{Li}^*$(0.98 MeV, T=1) in proton removal. This work is included in the Physical Review paper "Pi-Meson Induced Nucleon Removal to Discrete Final States."[2]

A theoretical effort[3] was made to explain this deviation from the expected value R = 3 by postulating that the outgoing nucleon underwent charge exchange to analog states in neighboring nuclei. This approach "explained," ad hoc, this lessened selectivity, so we looked for a definitive test of this theoretical model.

Analog charge-exchange is known to dominate the charge exchange process in nuclei. Thus if one were to populate an isospin-singlet state (i.e., T=0) no charge exchange is possible for the outgoing nucleon, and, so, no deviation from R = 3 is predicted in this model. We carried out an experimental to test this idea using the reaction $\pi^{\pm} + {}^{13}C \rightarrow \pi^{\pm} + n + {}^{12}C^{*}$, where both a T=0 state (at 4.44 MeV) and a T=1 state (at 15.11 MeV) were formed. Experimentally we found essentially the same energy dependence to the enhancement R, peaking at about R = 2 as it did in the previous neutron-removal experiment in Lithium. These results rule against this model where distortion effects are due to the outgoing nucleons undergoing charge exchange, as this model predicts the enhancements as follows: R(T=0) = 3 and R(T=1) ≐ 2. This work has been published[4] in Physical Review Letters under the title "A Definitive Test of Outgoing Nucleon Charge Exchange using the Reactions ${}^{13}C(\pi^{\pm},\pi N){}^{12}C$(4.44 MeV & 15.11 MeV)."

Single-neutron removal data to three distinct final states ${}^{6}Li$(3.56 MeV, T=1), ${}^{12}C$(15.11 MeV, T=1) and ${}^{12}C$(4.44 MeV, T=0) all show nearly the same enhancements of $R = \sigma(\pi^{-})/\sigma(\pi^{+})$ as a function of incident pion energy, with a peak value of about 2/3 of the predicted value (of 3). Although the origin of this 2/3 reduction is not yet understood (as we have ruled out a spurious theoretical model) we do observe a significant enhancement of about x2 for R (i.e., R ≐ 2). Further, this R ≐ 2 enhancement is a consistent feature of all three neutron-removal experiments to discrete final states, suggesting a fairly simple non-analog distortion may yet explain this effect.

In contrast to single-nucleon removal, multi-nucleon removal indicates a more complex reaction mechanism as its yields do not show a π-N resonant peaking with incident pion energy, as expected in a single step mechanism. This paper[5] has been accepted for publication by Physics Letters under the title "Energy Dependence of π^+ Induced Two- and Four-Nucleon Removal."

In addition to these gamma-ray measurements of nucleon removal, a kinematically complete measurement of quasifree proton removal was carried out using 255-MeV pions of both charged species on targets of ^{27}Al and ^{208}Pb, where the ratio of π^+ to π^- cross sections is 7.0±0.7 and 4.5±0.5, respectively. These values are less than the classical impulse-approximation value of 9 expected when both the proton and the pion are detected in the final state. These results have been published[6] in Physical Review Letters under the title "Coincidence Measurements of Quasielastic Pion Scattering by ^{27}Al and ^{208}Pb."

In summary, we conclude that nucleon removal by pions shows significant enhancements of π^- to π^+ cross sections (or vice versa) appropriate to the nucleon species being removed. These enhancements are less than expected from an un-modified simple impulse approximation, but the enhancements are large enough to establish pions as a potentially useful spectroscopic tool.

B. Pion Elastic and Inelastic Scattering

During the initial tuneup of the EPICS Spectrometer, while using a Carbon target, an unexpected peaking showed up in the experimental spectra corresponding to an excitation in ^{12}C of about 19.2 MeV. Figure 1 is a sum of experimental spectra for several angles near 70° in the Lab, for both charged species of incident pions at 164 MeV. So far we have not been able to explain this strong peaking at about 19.2 MeV in terms of the known states in ^{12}C. Preliminary data indicate a very strong favoring of this peak at 164 MeV, but falling much faster than the other spectral peaks for 100 MeV and 290 MeV (at 70.5° Lab). Also, the preliminary data show a monotonically decreasing cross section with scattering angle in contrast to scattering to the ground state, the 4.44 MeV state and the 9.64 MeV state.

An inelastic measurement in ^{18}O, using both charged pion species, was carried out to the first 2^+ state at 1.98 MeV, as part of the pion-spectrometer tuneup effort. Figure 2 is a sample spectrum showing this excitation using negatively-charged incident pions at 230 MeV. A ratio of π^- to π^+ differential cross sections, $R \doteq 2$, was observed at all angles measured as seen in Figure 3. An enhancement of as little as $R \doteq 2$ in this case is not surprising as this state is known not to be a pure valence-neutron excitation. However, this experiment is noteworthy as it is the first reported observation of such an enhancement in inelastic $\pi^\pm$ scattering. This work has been published[7] in Physical Review Letters under the title "Neutron Deformation Parameter by Comparative Study of π^- and π^+ Inelastic Scattering."

Elastic and inelastic scattering in the Calcium region was carried out primarily to test the experimental selectivity in promoting valence neutrons versus valence protons in the "Pauli Blocking" experiment (#229). Selectivity is expected in the inelastic formation of the strongly collective 2^+ and 3^- excited states, since, from an extreme single-particle point of view, neutrons completely fill the f-7/2 subshell in ^{48}Ca whereas the proton f-7/2 subshell is completely empty. Thus, the $0^+ \rightarrow 2^+$ positive-parity inelastic transitions (predominantly neutron f-7/2 → f,p) are dominated by the π^- interacting with valence neutrons, and the $0^+ \rightarrow 3^-$ negative-parity inelastic transitions (predominantly proton s,d → f,p) is dominated by π^+ interacting with valence protons. A quantitative analysis of this experiment will be based on the self-consistent Hartree-Fock wavefunctions of the ground state and the lowest-lying collective 2^+ and 3^- states as calculated by G. Bertsch.[8]

Figure 4 shows experimental pion spectra on ^{40}Ca for both charged pion species incident at 291.5 MeV, where these spectra have been summed over angle. The incident energy was chosen to enhance the inelastic excitations.[9] The 2^+ and 3^- states in ^{40}Ca are separated by less than the experimental resolution, but they may be extracted by computer fitting techniques. In any event, we expect comparisons may be made at their respective maxima, as the Blair phase rule predicts the angular distributions will be out of phase.

Figure 5 shows the angular distributions for each charged pion species, along with the "best fit" Kisslinger potential[10] elastic scattering calculations,[11] where the neutron and proton radii are held equal, as ^{40}Ca is the highest-Z self-conjugate nucleus. Differences between the π^- and π^+ angular distributions are well described and the Kisslinger "best fit" parameters for ^{40}Ca will be appropriately scaled for the other targets. This analysis is in progress.

Figure 6 shows experimental pion spectra using a ^{48}Ca target, for each charged pion species at an incident energy of 291.5 MeV, where the experimental spectra were summed over angle. Note the strong 2^+ and 3^- collective states are easily resolved, even at the present EPICS spectrometer resolution of about 350 keV, whereas these states could not be resolved by the (SUSI) pion spectrometer at the Swiss Institute (SIN) in Zurich.[12] Preliminary analysis shows a strong favoring of π^- for the 2^+ inelastic excitation at the first measured diffraction maximum, with less favoring of π^+ for the 3^- excitation at the first measured diffraction maximum, which occurs at a smaller angle than the maximum for the 2^+ state. This result is not surprising as the target, ^{48}Ca, has more neutrons than protons.

Figure 7 shows the elastic scattering angular distribution for each charged pion species incident on ^{48}Ca at 291.5 MeV.

Figure 8 shows the experimental pion spectra using a ^{44}Ca target, for each incident charged pion species at 291.5 MeV, where the experimental spectra have been summed over angle. The strong 2^+ and 3^- states are seen to be well resolved from one another. A lesser selectivity is expected for ^{44}Ca as it is -4 neutrons away from the closed (N=28) f-7/2 subshell. Similarly ^{54}Fe has been studied as it is +6 neutrons away from the closed f-7/2 subshell. Figures 9 and 10 show the elastic scattering angular distributions for ^{44}Ca and ^{54}Fe, respectively, for each species of charged pions incident at 291.5 MeV.

In summary, the differences between elastic scattering distributions for each charged pion species from ^{40}Ca appear to be well described using equal neutron and proton radii. Inelastic excitations in ^{18}O show an expected preference for π^- over π^+, and our preliminary data show the inelastic excitations in ^{48}Ca are behaving qualitatively as expected, with π^- favoring the 2^+ state and π^+ favoring the 3^- state.

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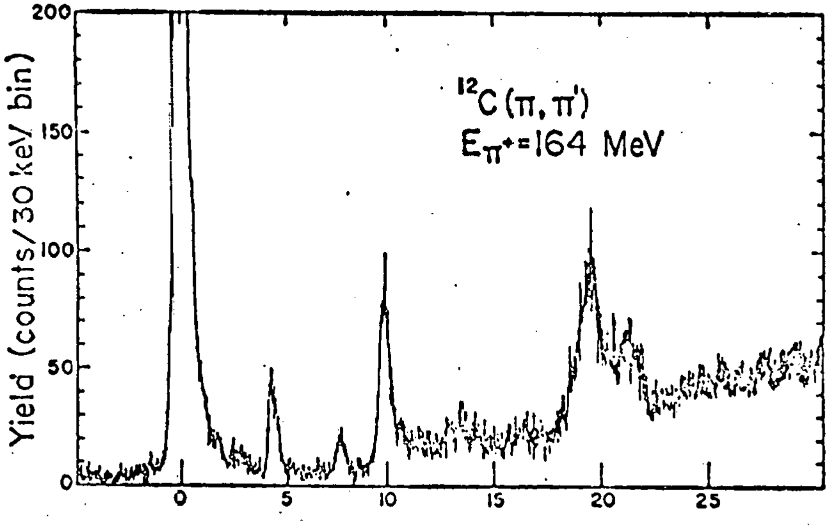


Fig. 1.

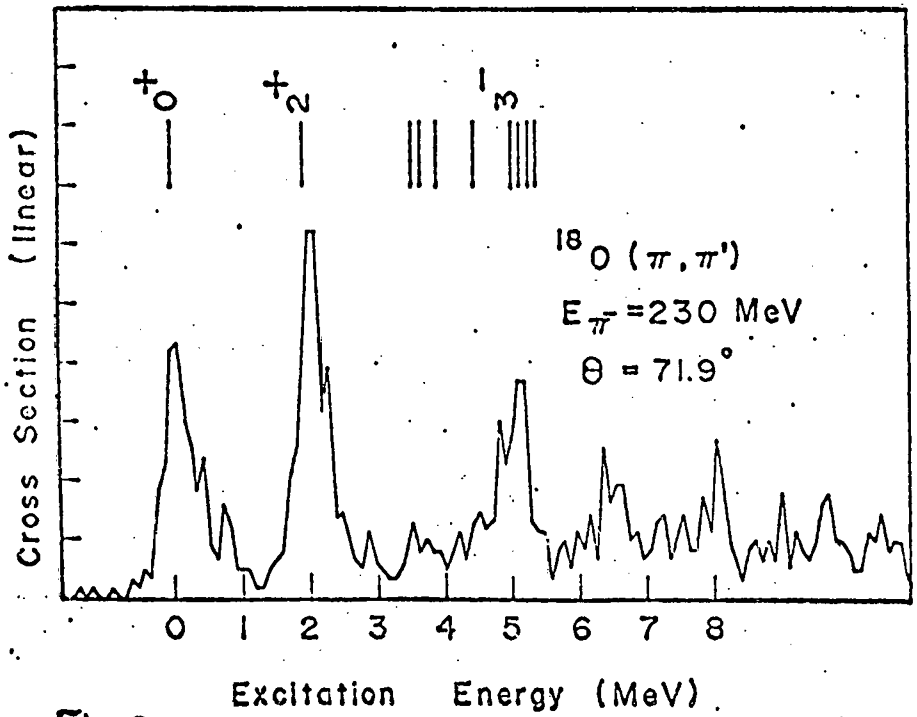
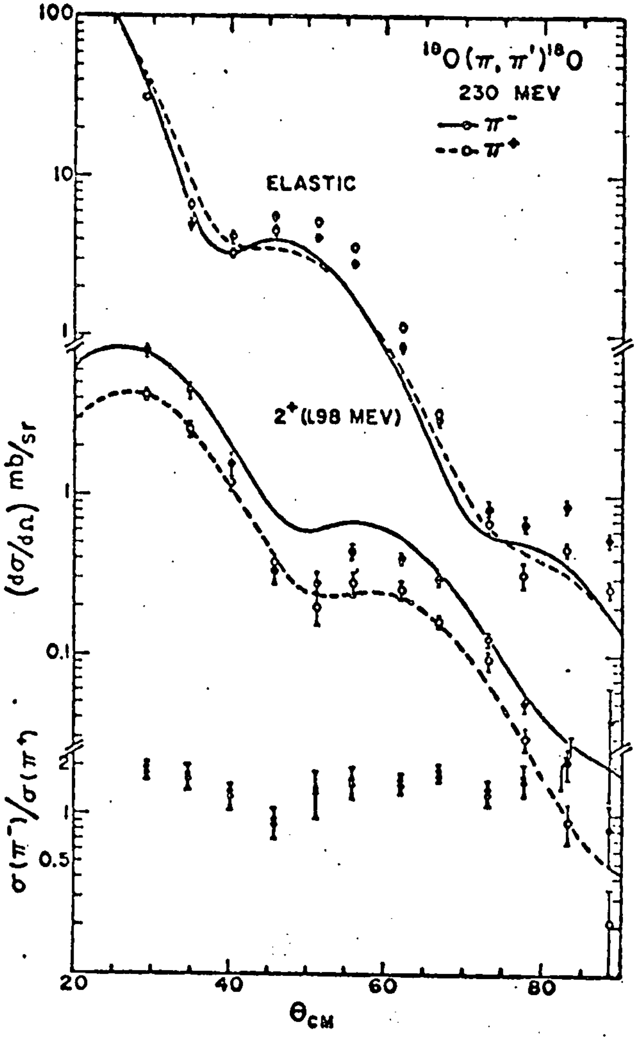


Fig. 2.



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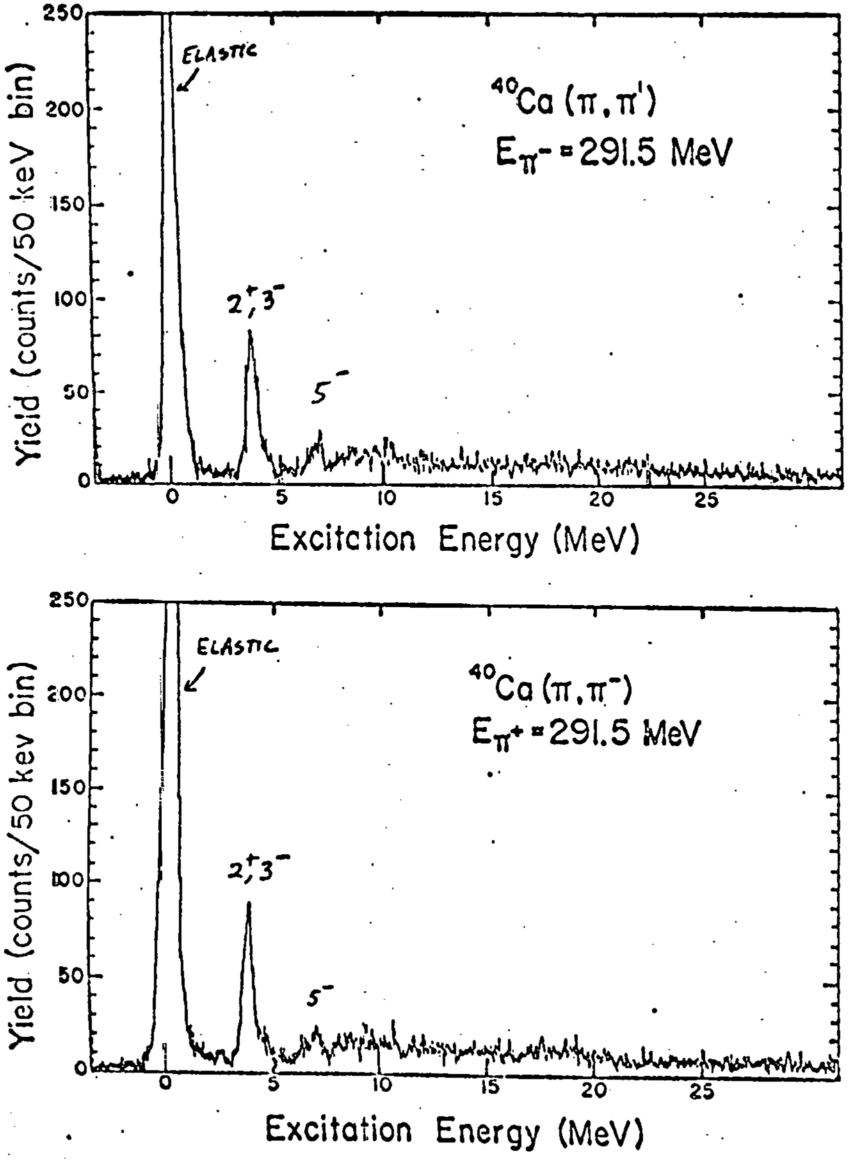
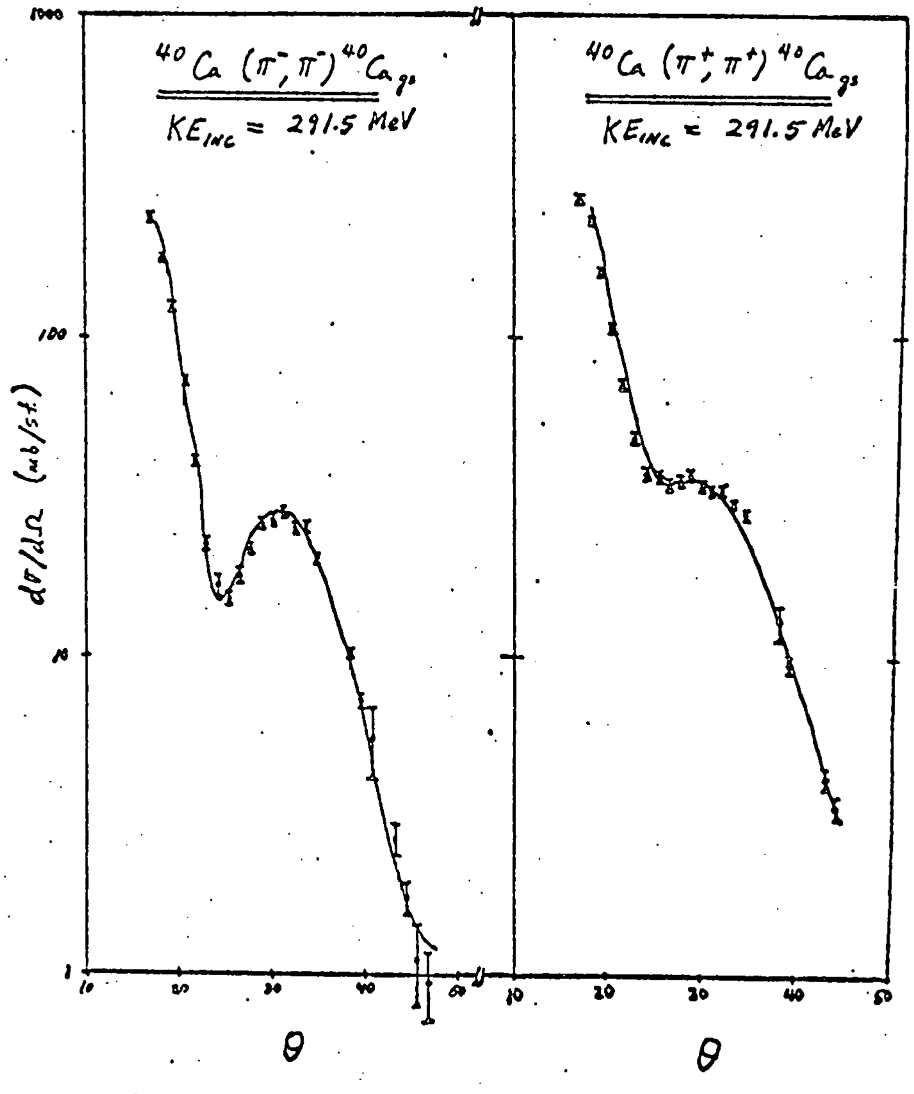


ELASTIC
^{40}Ca (π, π')
E_{π^-} = 291.5 MeV
2+, 3−
5−
Yield (counts/50 keV bin)
250
200
150
100
50
0
0
5
10
15
20
25
Excitation Energy (MeV)
ELASTIC
^{40}Ca (π, π⁻)
E_{π^+} = 291.5 MeV
2+, 3−
5−
Yield (counts/50 kev bin)
250
200
150
100
50
0
0
5
10
15
20
25
Excitation Energy (MeV)

Fig. 4.



^{40}Ca (π^-, π^-) ^{40}Ca$_{gs}$
KE_{INC} = 291.5 MeV
^{40}Ca (π^+, π^+) ^{40}Ca$_{gs}$
KE_{INC} = 291.5 MeV
dσ/dΩ (mb/st)
1000
100
10
1
10
20
30
40
50
10
20
30
40
50
θ
θ

Fig. 5.

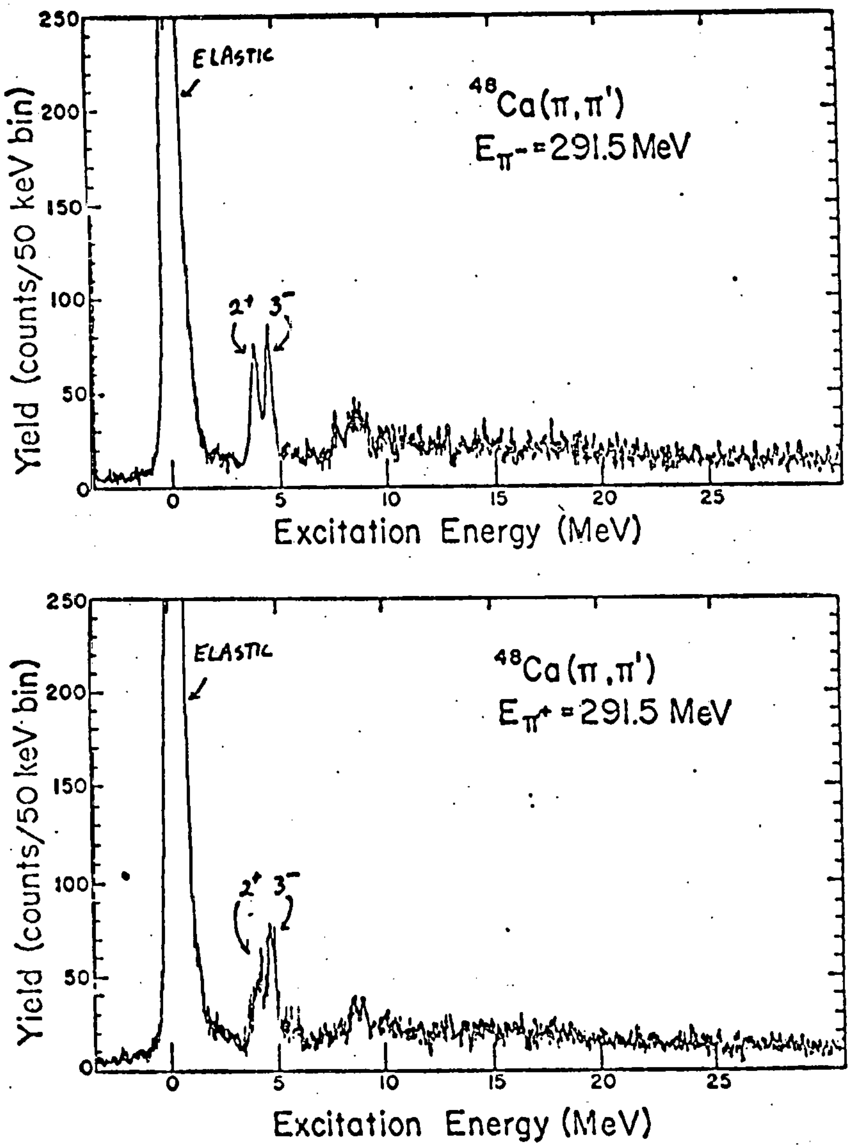

ELASTIC
^{48}Ca(π,π')
E_{π^-} = 291.5 MeV
2^+
3^-
Yield (counts/50 keV bin)
Excitation Energy (MeV)
0
5
10
15
20
25
50
100
150
200
250
ELASTIC
^{48}Ca(π,π')
E_{π^+} = 291.5 MeV
2^+
3^-

Fig. 6.

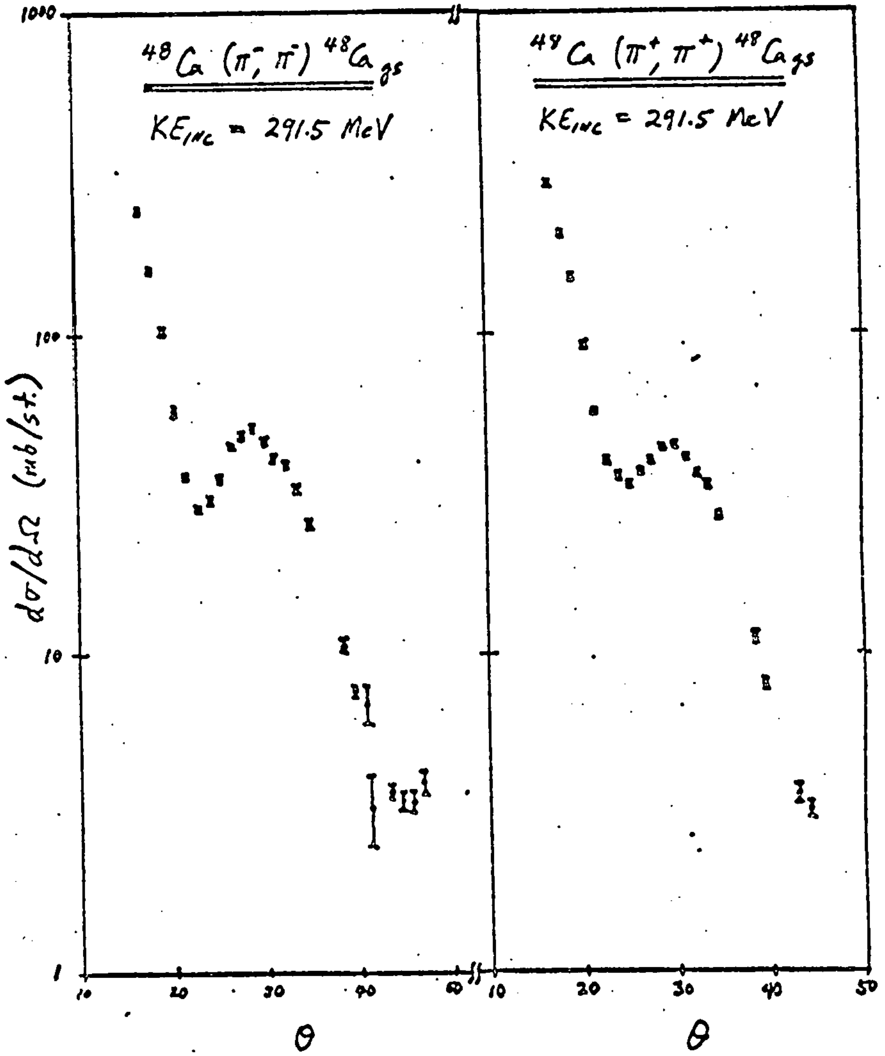

^{48}Ca (π^-,π^-) ^{48}Ca$_{gs}$
KE_{inc} = 291.5 MeV
^{48}Ca (π^+,π^+) ^{48}Ca$_{gs}$
KE_{inc} = 291.5 MeV
dσ/dΩ (mb/st.)
1000
100
10
1
10
20
30
40
50
θ

Fig. 7.

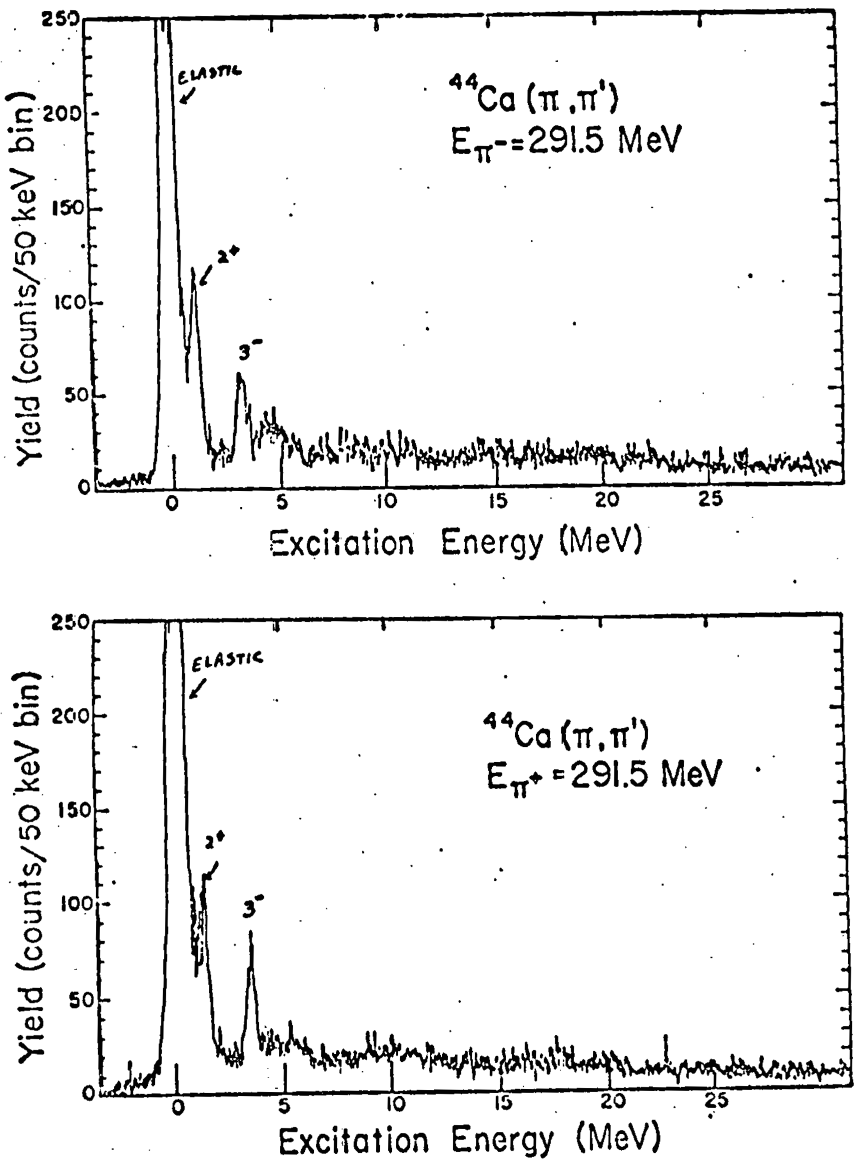

Yield (counts/50 keV bin)
Excitation Energy (MeV)
ELASTIC
2+
3-
^{44}Ca (π, π')
E_{π^-} = 291.5 MeV
E_{π^+} = 291.5 MeV
0
50
100
150
200
250
5
10
15
20
25

Fig 8.

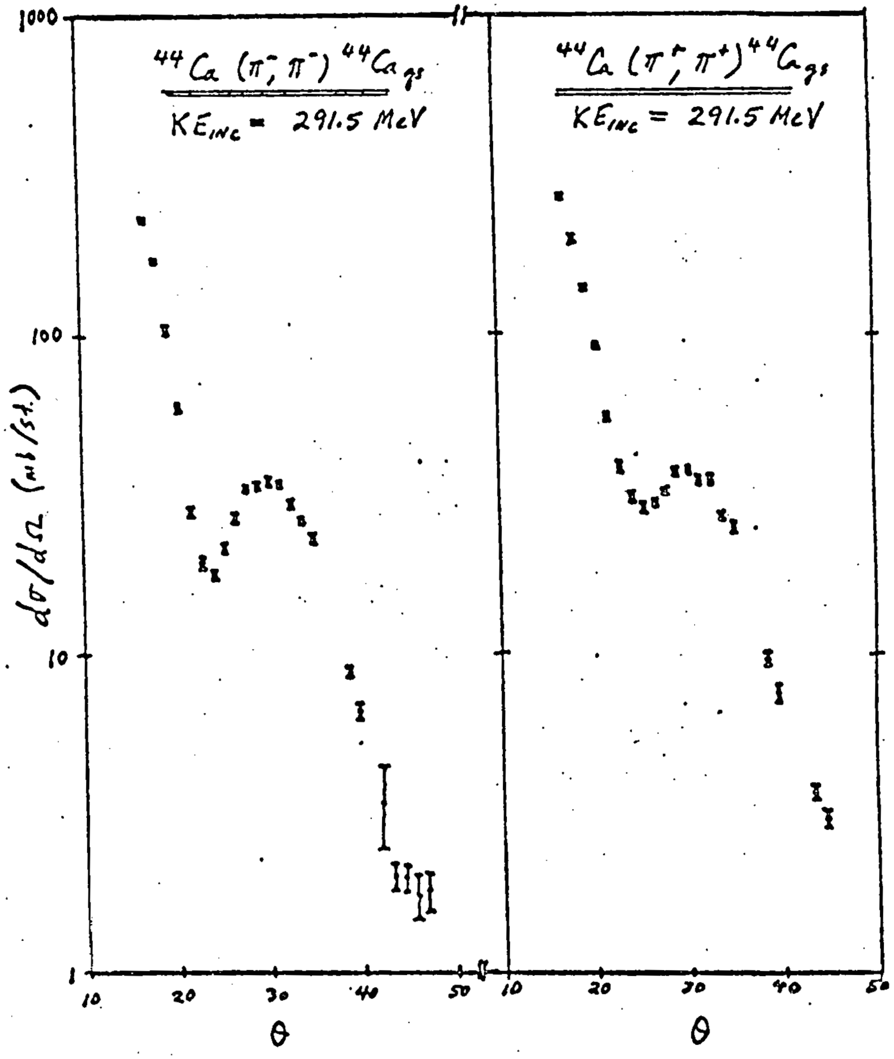

$^{44}Ca\,(\pi^-, \pi^-)\,^{44}Ca_{gs}$
KE_{INC} = 291.5 MeV
$^{44}Ca\,(\pi^+, \pi^+)\,^{44}Ca_{gs}$
KE_{INC} = 291.5 MeV
$d\sigma/d\Omega$ (mb/st.)
θ
1
10
100
1000
10
20
30
40
50

Fig. 9.

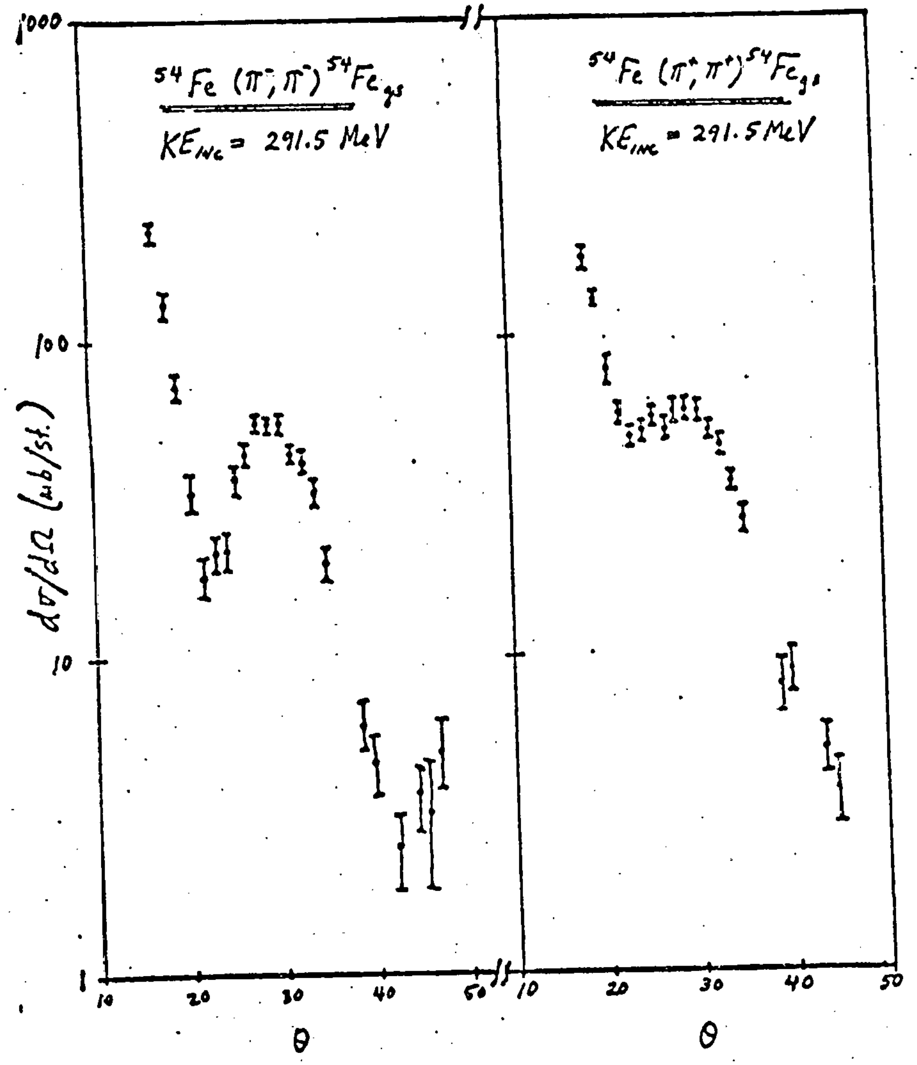

^{54}Fe (π^-,π^-) ^{54}Fe$_{gs}$
KE_{INC} = 291.5 MeV
^{54}Fe (π^+,π^+) ^{54}Fe$_{gs}$
KE_{INC} = 291.5 MeV
1000
100
10
1
$d\sigma/d\Omega$ (μb/st.)
10
20
30
40
50
10
20
30
40
50
θ
θ

Fig. 10.

IV. PUBLICATIONS DURING CONTRACT PERIOD

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VIII. PERSONNEL

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