MASTER

PION-NUCLEON INTERACTION AND MESONIC ATOMS

Progress Report

Glen A. Rebka, Jr. and Raymond Kunselman

University of Wyoming
Laramie, Wyoming 82071

February 1, 1977 - January 31, 1978

PREPARED FOR THE DEPARTMENT OF ENERGY
UNDER CONTRACT NO. E(11-1)-2197

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

EB
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ABSTRACT

During the year February 1, 1977, to January 31, 1978, the major activities under Task A have been (1) refinement of the analysis of data taken in Experiment #99, a measurement of the cross section for $\pi^- p \rightarrow \pi^- \pi^+ n$ near threshold, (2) extraction of the soft pion contribution to the cross section, (3) obtaining approval for Experiment #337, a continuation of #99 at lower incident energy and (4) improvement and modification of apparatus for Experiments #309 and #337. Though the analysis of data is not fully complete, integrated reaction cross sections twice the size of the previous measurement have been obtained with 1/3 the error. The soft pion contribution has been judiciously extracted, the parameter ξ determined to be between -2.0 and -3.5 and the isoscalar $\pi\pi$ scattering length a_0 found to be $0.35 m_\pi^{-1}$, a value consistent with those found in other processes. Additional measurements at 200 and 229 MeV to buttress these conclusions are approved and requisite modifications of the apparatus have been designed.

During the year February 1, 1977 to January 31, 1978, research under Task B, Mesonic Atoms has included analysis of muonic atom data from LAMPF, feasibility studies for a new beam in the stopped muon channel at LAMPF, analysis of antiproton-nucleus atomic data collected at BNL, and collection and analysis of data on the antiproton-proton atomic system at BNL.

TASK A: PION-NUCLEON INTERACTION AT LAMPF

During the year February 1, 1977, to January 31, 1978, the major activities under Task A have been (1) refinement of the analysis of data taken in Experiment #99, measurement of the cross section for $\pi^- p \rightarrow \pi^- \pi^+ n$, (2) extraction of the soft-pion contribution to the cross section, (3) obtaining approval for Experiment #337, a continuation of #99 at lower incident energy, and (4) improvement and modification of apparatus for Experiments #309 and #337. These activities are described in the paragraphs to follow.

Experiment #99 was planned so that the experimental system could be calibrated as a whole, incident beam through computer, by $\pi^+ p$ elastic scattering. Fragmentary calibrations of individual parts were avoided wherever possible and were only required to establish the constant shape of the fringe field, the excitation function for the spectrometer, and the absolute momentum scale of the spectrometer. Analysis of observations of elastic scattering and their comparison to the best available measured cross sections have therefore received considerable attention. Improved interpretation of observations of $\pi^+ p$ elastic scattering required improved interpolation of the measured cross sections. At 292 MeV and below, the "measured cross sections" were derived from the phase shift analysis of Carter, Bugg and Carter (Nuclear Physics B58, 378 (1973).) which had been primarily based on measurements

of $\pi^\pm p$ elastic scattering by Bussey, Carter, Dance, Bugg, Carter and Smith (Nuclear Physics B58, 363 (1973).) and also on measurements of $\pi^\pm$ total cross sections and of the $\pi^\pm p$ integrated charge exchange cross section referenced therein. A subroutine, composed of the phase shift expansion with coulomb corrections and of plausible functions of incident momentum which had been fitted to the phase shifts and coulomb corrections all given in the above article, computed the differential elastic $\pi^\pm p$ cross section for requisite incident momenta and scattering angles. Deleting one inconsistent result of the phase shift analysis before the functions were fitted, selecting more appropriate functions in a few cases and including the last two small parameters required by the original analysis substantially improved the subroutine. In a test of its accuracy, the various measured cross sections from which the phase shifts had been derived were compared to the cross sections computed by the subroutine. The $\pi^\pm p$ total cross sections and elastic cross sections were found to agree almost to the accuracy of the measurements between 90 and 310 MeV. Of course, these cross sections are the easiest to fit in this range, since they are dominated by the $\Delta(1232)$ resonance. The $\pi^\pm p$ elastic cross section agreed within the accuracy of the measurements for the three lowest and the highest energy; however the predictions of the subroutine were systematically 1.5% to 2% low for the five intermediate

energies. The π^-p total cross section agreed well on the average, but individual predictions deviated 1%, somewhat more than justified. The predictions for the π^-p integrated charge exchange cross section were systematically 1.0 to 1.5% low, again somewhat more than justified. These comparisons are displayed on the 6 pages of figures which follow. The subroutine may or may not contain a removable flaw. Its accuracy may well be limited by the consistency of the energy independent phase shift analysis itself. A manifest inconsistency has already been found in the analysis which limited the energy range for π^-p cross sections to 292 MeV. Greater difficulty for π^-p cross sections is not unexpected, since they result from a complicated combination of small phase shifts, none of which dominates. While improved accuracy will be sought, the subroutine for generating πp cross sections is more accurate in this energy range than others available. It will be described in a LASL report now in preparation and will subsequently be published.

Above 300 MeV where the subroutine discussed above was no longer useful, "measured π^-p elastic cross sections" were interpolated graphically from those reported by Ogden, Hagge, Helland, Banner, Detoeuf and Teiger (Physical Review 137, B1115 (1965).) and by Rugge and Vik (Physical Review 129, 2300 (1963).). More sophisticated interpolation was neither warranted nor attempted since the measurements of Ogden et al. had 4% errors. The errors which propagated into

Comparison with total cross section data of
Carter et al.

Elastic differential cross section, corrected for coulomb and coulomb-nuclear interference effects. Data of Bussey et al. at corresponding energies, from bottom to top, of 94.5, 114.1, 124.8, 142.9, and 166.0 MeV.

Data of Bussey et al. for incident pion kinetic energies, from top to bottom, of 194.3, 214.6, 236.3, 263.7, and 291.4 MeV.

Comparison with total cross section data of Carter et al (—); comparison with integrated charge exchange data of Bugg et al (···); and calculation of integrated elastic cross section (---).

Data of Bussey et al. for pion incident kinetic energies, from bottom to top, of 88.5, 119.3, 144.2, and 161.9 MeV.

Comparison with data of Bussey et al. at pion incident kinetic energies, from top to bottom, of 191.9, 219.6, 237.9, 263.7, and 291.5 MeV.

the calibration factors in this energy range due to limited knowledge of the elastic cross section are expected to dominate other errors in the experiment. These, however, can be eliminated when better information becomes available.

All elastic peaks measured by the spectrometer were reexamined and refitted to include high momentum pions which had been vetoed by the Cerenkov counter and to correct for lost "zoo" events which could not be neglected at higher counting rates. Although a few elastic measurements at high momentum changed as much as 16%, these had small weight in establishing the calibration which changed only a few percent at each incident energy. More significantly perhaps, the improved analysis made all observations of elastic scattering for a given incident energy, but different scattering angles, consistent to the accuracy of the measurements and comparison. The acceptance of the spectrometer is therefore thought to be independent of angle to 1 or 2%. The results discussed are evident in comparisons of observations of elastic scattering for three π^- beams used in the experiment with the predictions of the subroutine described above. These are shown in the three figures which follow. In these comparisons, the observations are fitted to the function only by adjusting a single scale factor which calibrates the system from the beam through the computer.

The analysis of data which yielded the doubly differential cross section $d^2\sigma/d\Omega dT$ for the π^+ meson in the reaction $\pi^- p \rightarrow \pi^- \pi^+ n$ was thoroughly reviewed to eliminate systematic

π^-p ELASTIC
w/o c veto
ANGULAR DISTRIBUTION
 $T_{\text{BEAM}} = 229 \text{ MeV}$

π^-p ELASTIC
w/o c veto
ANGULAR DISTRIBUTION
 $T_{\text{BEAM}} = 254 \text{ MeV}$

π^-p ELASTIC
w/o c veto
ANGULAR DISTRIBUTION
 $T_{\text{BEAM}} = 279 \text{ MeV}$

errors. The averaging effect of the 5% momentum bite of the incident beam was unfolded, the normalization was related directly to the CH₂ scattering monitor whenever possible, four measurements at 229 MeV and low π^+ momentum were deleted because the detector system had not functioned satisfactorily, and several measurements at 292 MeV for which the detector system had been improperly arranged were corrected. Inefficiency of the Cerenkov detector for electrons and efficiency for π mesons with high momentum were other possible sources of error in the analysis. The efficiency for electrons in a phase space much like that of the experiment was measured with an electron beam from the test channel at LAMPF and was well in excess of 99%. With such high efficiency, the errors from electrons not eliminated from the data were indeed negligible and no corrections were necessary. The efficiency for π mesons with momenta in excess of 220 MeV/c which was not completely negligible was contained in the analysis of the numerous observations of the π^+p elastic scattering made during the experiment. However, only three measurements of the doubly differential cross section required a small correction. Typical results of this analysis for three energies are displayed in the following figures which give the doubly differential cross sections at the locations indicated in T-cos θ space, as well as the doubly differential cross section divided by a "density" in T-cos θ space. This density also contains all other kinematic factors. The errors associated with each do

$$\frac{d^2\sigma^*}{d\Omega dT} \left(\frac{\mu\text{b}}{\text{sr-MeV}} \right) \text{ above } |\alpha^2|$$

$$\pi^- p \rightarrow \pi^+ \pi^- n$$

$$T_{\text{inc.}} = 229 \text{ MeV}$$

$\pi^- p \rightarrow \pi^+ \pi^- n$
 $\frac{d^2\sigma^*}{d\Omega dT} \left(\frac{\mu\text{b}}{\text{sr-MeV}} \right) \text{ above } |\alpha^2|$
 $T_{\text{inc.}} = 279 \text{ MeV}$

$$\frac{d^2\sigma^*}{d\Omega dT} = (PS) \cdot |\alpha|^2 \quad (\mu b / \text{sr-MeV})$$

$$T_{\pi^-}(\text{inc.}) = 330 \text{ MeV}$$

not include the uncertainty in calibration.

Several further improvements in the analysis of both elastic and inelastic data must still be investigated. Study of the loss of pions in the window, absorber and system of detectors at the output of the spectrometer is in progress and should be completed by the end of the contract year. A Monte Carlo subroutine which realistically calculates small angle scattering, energy loss and nuclear interaction as a particle traverses matter has been adapted with substantial improvements from a program developed by K. Ziock (private communication) and has been added to the general Monte Carlo program for transport through the spectrometer. Initial calculations show a surprisingly significant loss of pions at the higher momenta used in calibration with elastic scattering and some loss at the lowest from small angle scattering and straggling. When a more adequately realistic treatment of nuclear interaction has been written into the subroutine, corrections to the analyses of data which are expected to be 3 to 4% will be computed.

Another planned improvement in the analysis is more precise treatment of the loss of pions from decay in the spectrometer. While the decay of pions is easily calculated, the number of events which are saved through detection of the μ meson is uncertain and will be estimated with a Monte Carlo routine. The present uncertainty in the analysis due to pion decay

is thought to be 0.5 to 0.75% for elastic scattering and 1 to 2% for pion production. Other details which will be investigated are the adequacy of the skewed gaussian with a background to fit the elastic peaks and a possible change in efficiency of the surface barrier detectors with pion momentum. Should these effects be important, adequate corrections will be attempted.

An integrated reaction cross section was also derived from the doubly differential cross sections after they had been extrapolated to the inaccessible portions of phase space. A plausible function given by

$$|A + B T \cos \theta + C(T_{max} - T) \cos \theta + D T^2|^2$$

with A, B, C and D real was successfully fitted to the measured $|A|^2$ at each energy. C was set to zero except for the two highest incident energies. The product of the fitted function and the density was integrated and yielded the cross sections given in the following table with errors which include a generous contribution from the calibration. These integrated cross sections are also displayed on the following plot with a selection of the more accurate data previously available. At 292 MeV and above, the new cross sections agree well with the best of the earlier measurements; below, however, they are consistently larger and at 229 MeV become twice the value interpolated from older measurements. The disagreement has engendered much thought, discussion and review of our technique. At present, we believe that no substantial errors exist in our experiment

Integrated Reaction Cross Sections
and Soft Pion Interpolation

$T_{inc}(\text{MeV})$	$\sigma_R(\mu\text{b})$	$\Delta\sigma_R(\mu\text{b})$
228.6	90.7	5.9
252.7	203.3	8.7
278.9	403.9	15.7
291.5	546.3	21.9
330.4	1180.3	51.9
355.5	1900.9	81.7

$f = 81.8 \text{ MeV}$

$$\begin{aligned} \zeta &= -2.10 \text{ or } 6.62 \pm 0.10 \\ &\quad -2.10 \text{ is preferred and is used below} \\ a_0 &= 0.355 \pm 0.007 m_\pi^{-1} \\ a_2 &= 0.003 \pm 0.003 m_\pi^{-1} \end{aligned}$$

$f = 94 \text{ MeV}$

$$\begin{aligned} \zeta &= -3.50 \text{ or } 8.02 \pm 0.13 \\ &\quad -3.50 \text{ is preferred and is used below} \\ a_0 &= 0.345 \pm 0.007 m_\pi^{-1} \\ a_2 &= 0.033 \pm 0.003 m_\pi^{-1} \end{aligned}$$

and that the new result is correct.

The cross sections found in our almost completed analysis of data are already significant, new information and permit an orderly determination of the soft pion contribution to the matrix element. The doubly differential cross sections for the π^+ meson has not before been available so near threshold, and the integrated cross sections are much more accurate than earlier measurements. If the only contribution to the matrix element were that predicted by soft pion theory, the ratio $|\alpha|^2$ would be rigorously constant over $T\text{-}\cos\theta$ space and would also be independent of incident energy. The resulting integrated cross section would thus vary only with phase space and other kinematic factors. Since the results do not show such uniformity, the soft pion contribution must be extracted from an extrapolation to threshold.

E. Lomon has suggested that, above threshold, the squared modulus of the matrix element averaged over phase space might be expected to vary slowly with T_{total} , the sum of the kinetic energies of the outgoing particles in the center of mass. Polynomials in this variable multiplied by the integrated phase space and appropriate kinematic factors have therefore been fitted to the integrated reaction cross section. One such result is given in the following figure which displays the averaged, squared moduli of the matrix elements and the polynomial

$$a + b T_{\text{total}}^2$$

which has been fitted. Overly generous errors which include possible systematic problems in normalization are indicated. Also shown is the square root of the polynomial at threshold with error which we consider our best extrapolation of the modulus of the matrix element to threshold. Other polynomials successfully fitted have more freedom than justified by the present experimental uncertainties. However, their predictions at threshold are not markedly different and would give similar conclusions to those discussed below.

Soft pion theory predicts the matrix element at threshold with but two parameters, f_π and ζ . Since the pion decay constant f_π is determined by other processes to lie between 81.8 and 94 MeV, the present experiment can be interpreted within this uncertainty to yield ζ . An ambiguity between two values for ζ due to the unknown sign of the matrix element is resolved by requiring soft pion predictions for (1) the sign of the isoscalar, S-wave $\pi\pi$ scattering length to agree with earlier results and (2) the cross sections for $\pi^-p \rightarrow \pi^+\pi^-n$ and $\pi^+p \rightarrow \pi^+\pi^+n$ to agree in order of magnitude with the rough measurements available near threshold. Conclusions for the extreme values for f_π are shown in the preceding table, and values for ζ , a_0 , and a_2 fall between these limits for the entire range of f_π . The values of ζ between -2.1 and -3.5 are clearly

inconsistent with the Weinberg Lagrangian ($\zeta=0$) and the Schwinger Lagrangian ($\zeta=1$), and thus remove these from consideration. A particularly simple effective Lagrangian among the infinitude given by Olsson and Turner requires $\zeta = -2$; however, such elegance cannot be considered compelling. The isoscalar, S-wave $\pi\pi$ scattering length a_0 varies but slightly between 0.355 and 0.345 m_π^{-1} for the range of f_π , all values compatible with determinations from other processes. Its insensitivity to f_π occurs fortuitously in this particular range of ζ for which a_0 strongly dominates the matrix element. Thus a change in f_π is almost exactly countered by the resulting change in ζ . If indeed soft pion theory is only roughly correct, as might well be true, the present determination of a_0 might still be substantially correct so long as it continues to dominate the matrix element. Values of a_2 vary between 0.003 and 0.033 m_π^{-1} as f_π changes but are all extremely small. For all other charge states except $\pi^- p \rightarrow \pi^0 \pi^+ n$, the soft pion contribution to the matrix element results only from a "contact term" and a term in a_2 which tend to cancel for $a_2 > 0$. The fortunate prediction of an extremely small contribution which is experimentally consistent with zero provides an incisive test for soft pion theory. No evidence contradicts this conclusion, but available measurements are hardly definitive and do not permit a convincing extrapolation to threshold. Unfortunately for the future experiment,

measuring zero, while particularly incisive, is not so satisfying. The errors for f , a_0 and a_2 shown in the table result only from generously estimated errors in the measurements. Uncertainties in the strong coupling constant and g_A/g_V have not been included. Also the extremely serious uncertainties of extrapolating the doubly differential cross section in $T\text{-}\cos\theta$ space and the averaged squared modulus of the matrix element to threshold are still to be treated seriously. A crude estimate suggests that a 20% uncertainty in f and an 8% uncertainty in a_0 might be the maximum anticipated. These can only be reduced by more complete measurements. Finally, the validity of soft pion calculations for this reaction must be resolved by measurement of another charge state and by deeper theoretical understanding.

The most serious uncertainties in interpretation of the present experiment can only be removed by reducing the extent of extrapolation required. Improved coverage of $T\text{-}\cos\theta$ space with measured doubly differential cross sections at 229 MeV incident energy would lessen the extent of extrapolation needed to determine the integrated reaction cross section and measured cross sections at 200 MeV incident energy would lessen the extent of extrapolation to threshold. A proposal for Experiment #337, "Measurement of the Cross Section for $\pi^- p \rightarrow \pi^- \pi^+ n$ at 200 and 229 MeV," which requested 600 hours for these additional measurements was submitted to

LAMPF during the past year and has been approved. The additional measurements are expected to be made during the coming year. Several modifications to the experimental system required for the new measurements are already in progress. Sampling of $T\text{-}\cos\theta$ space has been restricted by the 32° forward limit in the rotation of the spectrometer and the 70 MeV/c lower limit in the momentum of pions which could be detected. The forward limit of rotation has been reduced to 20° by moving the position of the spectrometer 6" downstream in P^3 with no deleterious effect on the predicted beam spot and by designing a new scattering chamber with larger diameter which should also reduce background from its windows. The scattering chamber has already been designed schematically, has been engineered and is now being detailed. The minimum momentum for detected pions will be reduced to 60 MeV/c or less by using 1/16" thick scintillation counters mounted in a dark box with a minimum of individual wrapping and by using a stopping scintillation counter of appropriate thickness for the lowest momenta. The thinner, unwrapped counters will also absorb fewer pions at higher momenta and thus reduce the difficulty of the requisite correction. Sample counters are now being constructed and tested. A rectangular tank has been constructed for the fluoro-carbon, threshold Cerenkov counter and will soon be tested. The performance of the counter, although previously entirely satisfactory with a

cylindrical tank, is expected to be far less sensitive to alignment and hence more reliable in the field. Previous experience indicates that the role of the Cerenkov counter in eliminating a background of electrons will become more crucial in the new measurements at the lower 200 and 229 MeV incident energy. Finally a set of Si(Li) detectors, 1 cm x 4 cm x 600 μ m, will replace the old silicon surface barrier detectors. The new detectors are expected to have similar properties to the old which have become unreliable, but will be a bit longer to better cover the image in the focal plane and a bit thicker to increase the signal to noise for minimum ionizing particles. The old detectors have always had excellent performance when working, but suffer about 10% failure whenever the vacuum chamber is evacuated. Apparently this problem is generic with surface barrier detectors which has been recognized at other laboratories as well, not an unusual problem with our set.

All of the modifications discussed above will vastly improve Experiment #309, " π^+ and π^- Double Charge Exchange Disintegration of ^{16}O , ^{40}Ca and ^{208}Pb ," for which 400 hours have been approved during the past year and which is expected to run shortly after Experiment #337. The entire experimental system seems ideally adapted to this measurement and will be used without modification except for replacing the cryogenic target with a remotely controlled ladder of solid targets. The target ladder has been designed along with the

new scattering chamber and is also being detailed. Not only is the hardware used previously well adapted, but the programs for analysing data which have been developed thus far are also almost immediately applicable. Only some specialized parts need be deleted. Hence, preparations for this experiment are also well under way.

During the reporting period, the principal investigator for Task A (G. A. Rebka, Jr.) has devoted approximately 60% of his time to this research. In addition to the publications listed below, a report on the computer subroutine to interpolate measured elastic cross sections has been in preparation and colloquia or seminars have been given at LAMPF, Yale University and University of Massachusetts (Amherst). Publications during this period are:

"The Measurement of the Elastic Cross Section for Positive Pions on Carbon at 142 MeV" (Alden T. Oyer), Los Alamos Report, LA-6599-T, C00-2197-50.

"Measurement of the Cross Section for $\pi^- + p \rightarrow \pi^- + \pi^+ + n$ near Threshold" (Bjork, King, Oyer, Rebka, Walter, Gram, Shively, Bordner, Carawon, and Lomon), Bul. Amer. Phys. Soc. 22, 653 (1977). C00-2197-51.

"A Measurement of the Cross Section for $\pi^- p \rightarrow \pi^- \pi^+ n$ Near Threshold, Implications for $\pi\pi$ Scattering Lengths" (Gram, Shively, Bjork, King, Oyer, Rebka, Walter, Bordner, Carawon and Lomon), abstract for "7th International Conference on High-Energy Physics and Nuclear Structure," Zurich (1977). C00-2197-52.

"Pion-Nucleon Interaction and Mesonic Atoms, Progress Report 1977" C00-2197-53.

"Pion-Nucleon Interaction and Mesonic Atoms, Science Information Exchange 1977" C00-2197-54.

TASK B: MESONIC ATOMS

The efforts on mesonic atoms for 1977 have been on experiments at LAMPF and BNL.

From the LAMPF data the analysis has continued on the distorted nuclei. The data from muonic atoms of Dy and Pd have been completed and the analysis on Re is continuing. The measurements of the muonic X rays were of the 4-3, 3-2, and 2-1 muonic transitions. From the 3d hyperfine structure (h.f.s.) we determined the spectroscopic quadrupole moment of the ground state essentially in a model independent manner. This was because the 3d state wavefunctions do not penetrate the nucleus to a great deal and the finite - size nuclear-charge corrections were calculable confidently. From the 2p h.f.s. we usually determined the ground state quadrupole moment as well as that for the first excited state and that for the transition moment connecting the two states. For the Dy the data was also sensitive to the second excited state and the quadrupole moment for that state and the transition moment to the ground state were determined. These determinations depend as well on the nuclear charge parameters which were determined at the same time. The intrinsic hexadecapole moment was determined from the 3d h.f.s. The nuclear charge density was described by a generalized five-parameter Fermi distribution. The best fit of the parameters to the data was determined with the h.f.s. as well as fine structure and absolute energies included.

These targets were each run along with a Pb target that served as a "beam on" energy calibration for each of the unknown targets. This procedure allowed for corrections because of gain shifts and allowed very precise energy determinations. This led to about a one-percent determination

in the quadrupole moment.

The feasibility study for another beam in Cave C of the SMC at LAMPF was continued. Approval was given for a run on our experiment 173 (CIT) with a high priority rating. The experiment would be a pionic atoms study with a crystal spectrometer. Several studies have been made to study the stopping rates, the necessary background shielding, and optimal channel configurations. The studies have led to necessary requirements to do the experiments at the present LAMPF proton beam levels (about $300\mu\text{A}$). The protons can produce enough pion stops and hence pionic atoms with sufficient signal to noise. The desirable additions would be a vacuum pipe for the last section as well as the front sections, a thicker more efficient pion production target, and a realistic shielding of the detectors from neutrons.

The pionic atoms measurements were deemed to be of interest and the cave arrangements possible so that we were granted approval to proceed.

From the BNL data we have completed the analysis of antiprotonic atoms data for atomic numbers from 3 to 70. The results were an antiproton mass measurement and an antiproton-nucleus interaction measurement. The mass is in agreement with the proton mass which is in agreement with expectations of the CPT theorem. The magnetic moment was also measured to be in agreement with the CPT expectations. The semiphenomenological fit of the data to an optical model potential yielded an effective scattering length. It was interesting to note that a single complex parameter sufficed for all nuclei.

The antiproton-proton X-ray studies were continued at BNL with adequate progress made to warrant continuing the efforts. The antiproton beam was stopped in targets of both gaseous and liquid hydrogen. The hydrogen targets were viewed with high-resolution Si(Li) solid-state detectors which were sensitive to X rays between 3 &

30 keV that would be emitted by the antiprotons during their atomic cascade. Upper limits on the yields of the K_{α} $\bar{p}p$ X-ray transitions were made and these were below predicted yields. The predicted yields were recalculated and revised downward, after these preliminary results. We had possible evidence of the uninteresting 3d-2p transition X rays at 1.75 keV but will improve the collection efficiency to below 3 keV to confirm this in the future. The 3d-2p transition should not be affected by the strong interaction but the 2p-1s should be affected. The unshifted energy would be 9.41 keV and we would have been sensitive to either a positive or negative shift representing an attraction or a repulsion. The target was modified during the experiment after careful studies that used gaseous He and Ne as the target gas. When these gases were exposed to the same beam of antiprotons as the H target, we measured spectra that served as a confirmation of an energy calibration and of our stopped $\bar{p}$ signature. The Ne target was so "dense" compared to the H target that the X rays were produced quite rapidly.

The detectors and electronics worked so well at BNL that we began preparations for a $\pi \bar{p}$ atomic X-ray measurement at SREL. Modifications on a target were begun and the remainder of the apparatus can be used unchanged.

The final progress to report on this period is in the area of data acquisition. Following the suggestions of the LAMPF computer committee we have obtained a large part of a PDP 11-34 data acquisition system. The equipment included the console, central processor, a tape unit, and a Camac unit. Rudimentary Camac modules were obtained so that we have begun program development.

During the reporting period, the principal investigator for Task B (R. Kunselman) devoted 67% of his time to this research.

PUBLICATIONS

- C00-2197-45 Pionic 4f-3d transitions in ^{148}Nd and ^{150}Nd and the neutron isotope shift, (Kunselman, Roberson, Powers, Boehm, Miller, Zehnder), Phys. Rev. C15, 1801 (1977).
- C00-2197-46 A Precision Determination of the Radial Charge Parameters and the Quadrupole Moment of ^{181}Ta Using Muonic X-Rays, (Powers, Boehm, Zehnder, Kunselman, Roberson), Nucl. Phys. A278, 477 (1977).
- C00-2197-47 Strong interaction and mass measurements using antiprotonic atoms, (Roberson, King, Kunselman, Miller, Powers, Barnes, Eisenstein, Sutton, Lam, Cox, Eckhause, Kane, Rushton, Vulcan, Welsh), Phys. Rev. C16, 444 (1977).
- C00-2197-48 A Muonic X-Ray Determination of the Nuclear Charge Distribution of ^{161}Dy , (Powers, Boehm, Hahn, Miller, Vuilleumier, Wang, Zehnder, Kunselman, Roberson), Seventh Intl. Conf. on High Energy Phys. and Nucl. Structure, Zürich (1977) p. 273.
- C00-219-49 Experimental Studies of the Formation of $\bar{p}p$ Atoms in Gaseous and Liquid Hydrogen, (Eckhause, Giovanetti, Kane, Lindemuth, Pandey, Rushton, Vulcan, Welsh, Barnes, Craig, Eisenstein, Sherman, Sutton, Wharton, Miller, Powers, Kunselman), Seventh Intl. Conf. on High Energy Phys. and Nucl. Structure, Zürich (1977) p. 300.
- C00-2197-53 Pion-nuclear Interactions and Mesonic Atoms, Progress Report, 1977, (Rebka, Kunselman).
- C00-2197-54 Pion-nuclear Interactions and Mesonic Atoms, Science Information Exchange 1977, (Rebka, Kunselman).