PION-NUCLEON INTERACTION AND MESONIC ATOMS

Progress Report

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February 1, 1976 - January 31, 1977

PREPARED FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
UNDER CONTRACT NO. E(11-1)-2197

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ABSTRACT

During the year February 1, 1976 to January 31, 1977, the major activities under task A have been (1) completion of all equipment and programs necessary for operating Experiment #99, measurement of the cross section for $\pi^- + p \rightarrow \pi^- + \pi^+ + n$ near threshold, (2) operation of Experiment #99, (3) preliminary analysis of the data gathered, and (4) preparation of a proposal for an exploratory measurement of π^+ and π^- double charge exchange in the disintegration of ^{16}O , ^{40}Ca , and ^{208}Pb . The initial, rough analysis of all data in Experiment #99 should be completed by the end of the contract year and will yield a total cross section for pion production at 6 energies between 225 and 350 MeV with 10% accuracy. In addition, the doubly differential cross section will be far more detailed than has previously been available at these energies.

During the year February 1, 1976 to January 31, 1977, research under Task B, Mesonic Atmos, has included (1) collection and analysis of muonic atom data at LAMPF, (2) feasibility studies for a further beam in the stopped muon channel at LAMPF, (3) analysis of antiprotonic atom data collected at BNL, and (4) collection of data on the antiproton-hydrogen system at BNL.

TASK A: PION-NUCLEON INTERACTION AT LAMPF

During the year February 1, 1976 to January 31, 1977, the major activities under Task A have been (1) completion of all equipment and programs necessary for operating Experiment #99, measurement of the cross section for $\pi^- + p \rightarrow \pi^- + \pi^+ + n$, (2) operation of Experiment #99, (3) preliminary analysis of the data gathered, and (4) preparation of a proposal for an exploratory measurement of double charge exchange from complex nuclei. In addition, analysis of the $\pi^- + C$ elastic scattering data taken two years ago has been refined, has been presented in a thesis, and will be published shortly. These activities are described in the paragraphs to follow.

Several improvements in the apparatus and procedures for Experiment #99 were completed early in this period. A new ion chamber and a two arm scintillation counter telescope were constructed to improve monitoring of the pion beam. The ion chamber had sensitivity greater than those previously available and was designed to mount securely to the vacuum pipe at the last quad of P³. The counter telescope was mounted downstream of the experiment and detected scattering from a polyethylene target at 90° to the left and to the right. These monitors had somewhat complementary virtues and liabilities. Changes in the contamination of the beam affected the ion chamber, but not the scattering monitor, while changes in the final steering and focus affected the scattering monitor slightly, but not the ion chamber. Also, the scattering monitor could be electronically corrected for dead time, while the ion chamber could not. Both monitors were logged and compared whenever possible, and only on rare occasions was any discrepancy detectable.

With these instruments, we believe that the relative intensity of the beam was monitored with about 1% accuracy, which was a distinct improvement over earlier efforts.

The electronic system was modified and a program written to more fully incorporate a mini-computer (PDP 11-20) into the spectrometer system. The computer provided the capacity and versatility to sort and to store events from the detectors in several arrays. These assisted in particle identification, kept track of "zoo events", and presented the principle data free from "zoo events". It also read scalers and the voltage on the spectrometer shunt periodically, and wrote all data on paper tape at the end of each run. While our application of the computer was rudimentary by some standards, it was most reliable and effective in collecting and accurately recording the data.

Several other items of hardware were slightly modified. The liquid hydrogen target was remounted to permit more accurate positioning, the LAMPF standard scintillation counters were rebuilt for greater mechanical reliability, and a "thick" scintillation counter was constructed and used as a stopping counter for low momentum π mesons to improve signal to noise. Each of these contributed to the accuracy, reliability, and efficiency of the experiment.

From the middle of June through the middle of September, the major batch of data for Experiment #99 was gathered. The doubly differential cross section $\frac{d^2\sigma}{dpd\Omega}$ for $\pi^- + p \rightarrow \pi^+ + \pi^- + n$ was measured at six incident beam energies between 225 and 350 MeV and at about 20 points for each energy distributed roughly uniformly in the accessible portion of the center of momentum phase space for the π^+ meson. At most of these points,

the true counting rate for production events, the difference between the counting rates with the target full and empty, was determined with about 10% statistical accuracy. This accuracy ranged, however, between 5% for high beam energies and favored locations and 15% or 20% for low energies and unfavored locations. These measurements constitute unprecedented detail in the doubly differential cross section for this reaction and are expected to yield the total cross section with about 6% accuracy, except possibly at 225 MeV, where the statistical errors are greater and the coverage of phase space is not so complete.

The intensity of the π^- beam required to normalize these production cross sections was determined by observing π^-p elastic scattering with the spectrometer and comparing the observation to the measured elastic cross section. For each energy, a measurement was made every 10° for as many angles as permitted by the 300 MeV/c momentum limit of the spectrometer. At present, all of these calibration data have been fairly thoroughly analysed. Their comparison to measured cross sections for beam energies between 225 and 300 MeV yield a calibration which is reliable to about $\pm 5\%$. Most of the uncertainty is thought to be in extrapolating the measured cross section to the momenta and angles for our experiment, not in the data itself. The extrapolation is being improved and a calibration reliable to $\pm 2\%$ should be possible for these energies. For beam energies above 300 MeV, a serious extrapolation has not yet been attempted, but the data have been analysed with no difficulties.

A set of observations of π^+p elastic scattering at 250 MeV/c was made at 10° intervals over the angular range of the spectrometer to determine the variation of acceptance with angles. Such variation will result

from the change in projection of the irradiated volume in the target with angle and from any misalignment of the target or beam. These data have been analysed, have been compared to the measured cross section, and have indicated no change in acceptance within the 5% reliability of the extrapolated cross section. When the extrapolation has been improved, we expect to find a few percent variation which has been indicated by our Monte Carlo studies of the spectrometer and will use the result to correct the measurements of both elastic scattering and pion production.

In a calibration procedure that has now become routine, another set of observations of π^+p elastic scattering was made with the spectrometer at 50° and in 0.5% intervals of the central momentum of the spectrometer to sweep the elastic peak through each detector in the focal plane. The position, width and area have been determined for the elastic peak seen by each detector and these yield the relative efficiency of each channel in the focal plane and the dispersion of the spectrometer all to about 1% accuracy. Results from this calibration have been used throughout the analyses of elastic scattering and pion production discussed earlier.

Before removing the spectrometer from the floor, the hydrogen target was replaced with a bare ^{241}Am α -source which was located precisely at the beam height. No other changes were made in the apparatus. With these α -particles and with the same detectors used in the experiment, the relation between the central momentum of the spectrometer and the magnetic field was established to about 0.1%. This relation is essential for properly interpreting and presenting the results of our experiment, but has also produced the best available calibration of the momentum of the p^3 channel. Our collection of data on πp elastic scattering has enabled us

to calibrate the channel at 8 momenta between 150 and 475 MeV/c with an estimated $\frac{1}{4}\%$ error. The calibration will be made available to other P^3 users through a LASL report, as soon as they are not likely to be changed by more refined analysis. Meanwhile they are available as required via private communication.

The initial analysis of the pion production data is presently in progress and should be completed by the end of the contract year. This first attempt should yield total cross sections with about 10% accuracy, an improvement over the 20% accuracy now in the literature. In addition, the doubly differential cross section will be far more detailed than has previously been available. We hope to present these preliminary results at a spring APS meeting.

A proposal has been submitted to LAMPF for a subsequent experiment which will use the "99 spectrometer" and associated instrumentation and which can be successfully conducted with the 100 μ A primary beam now available. The experiment proposed will be an exploratory measurement of π^+ and π^- double charge exchange in the disintegration of ^{16}O , ^{40}Ca , and ^{208}Pb , mostly below the production threshold. Like the measurement of pion production, a pion with one charge will be incident on the target and a pion with the other charge will be detected and identified with the spectrometer system. The range of pion momenta in the spectrometer will be similar to those in the previous experiment and the cross sections, according to the scanty data available, will be the same order of magnitude. Only the targets and the incident energies will be different. Analysis of the data will be carried out with the same programs developed for the previous experiment. Hence, no difficulties are anticipated in making the measurements, and their results should be quickly available.

This exploratory effort will provide a body of data which should stimulate theoretical curiosity to understand the roles of double scattering, $\pi-\pi$ scattering, 3,3 resonance exchange, and nucleon-nucleon correlation in the process. If the results of experiment and theory prove interesting, the subject can be pursued more thoroughly and more accurately when LAMPF operates with 1 mA of primary current.

During the reporting period, the principal investigator for Task A (G. A. Rebka, Jr.) has devoted approximately 60% of his time to this research. Also during this period, a doctoral thesis entitled "Measurement of the Elastic Cross Section for Positive Pions on Carbon at 142 MeV" has been submitted to the University of Wyoming by Alden T. Oyer and has been accepted. Publications during this period are:

"Pion-Nucleon Interaction and Mesonic Atoms,
Progress Report 1976" C00-2197-43.

"Pion-Nucleon Interaction and Mesonic Atoms,
Science Information Exchange 1976" C00-2197-44.

TASK B: MESONIC ATOMS

The efforts on Mesonic Atoms for 1976 have been at LAMPF and BNL.

The muonic atom measurements at LAMPF after the "great" shut down have continued the nuclear structure studies. Targets of ^{187}Re , Pd, and Dy have been run along with a standard Pb target. All targets were run together under identical conditions so that the Pb target served as a "beam on" energy calibration for the other three unknown targets. This procedure allows for corrections because of gain shifts and allows a very precise energy determination. The muonic atom x rays were observed and collected by means of large solid state detectors. The higher energy x rays from transitions of the muon near to the nucleus lead to determinations of the nuclear charge distribution parameters because of large overlap of nuclear charge distributions. These higher energy x rays are influenced by the nuclear quadrupole moment but a determination of this moment depends on the nuclear model one chooses. The lower energy x rays from transitions of the muon far from the nucleus are not as dependent upon the nuclear model and lead to more precise determinations of moments. The values of moments that were determined were in agreement with tabulated values but were more precise than those from other techniques. More precise moments are useful in theoretical calculations using various nuclear models. The nuclear charge distributions are similarly in agreement and usually more precise than previous measurements. The recent improvements in data collection equipment and detectors has helped lead to the improved quality of the measurements but the increased stopped muon fluxes now available at LAMPF are also important.

A feasibility study was undertaken to see what would be necessary to develop a new stopping beam from the upstream portion of the muon channel at LAMPF. The two present beams are extensively used and heavily scheduled. It was planned in conjunction with the Cal Tech group to install a bent crystal spectrometer for pionic atom and muonic atom measurements. This apparatus is not as mobile as solid state detectors and is better left in place for a period of time to make a series of measurements. We determined the various backgrounds and made "range" curves to determine the stopping rates available. The rates at the present intensities of LAMPF were extrapolated to expected rates and suggestions were made for beam magnets that would improve the rates. We were able to collect a pionic-atom x-ray spectrum with the somewhat crude setup available. At the same time as the testing was conducted in the proposed new area, we collected data in the old area. The channel magnets after the new area can be optimized separately from the earlier beam magnets needed for the new area. Acceptable stopping intensities were available and x-ray spectra were collected. Requests for beam time to setup equipment and make measurements were tentatively approved.

The antiprotonic atom measurements at BNL have continued. The analysis of the antiprotonic atom data for high Z nuclei was completed and the results were being studied. Measurements were made of the antiproton mass and of the antiproton-nucleus strong interaction.

The analysis has required several precise energy calculations. These include radiative corrections, as vacuum polarization, finite nuclear size corrections, nuclear polarization corrections, electron screening corrections, and a correction for the anomalous magnetic moment of the antiproton. The magnetic moment was also determined to be in agreement with previous measurements which agree with the CPT theorem expectation that the antiproton and

proton have magnetic moments of opposite sign. Calculations were made for the higher moments of nuclei. When these were significant they were also included. All corrections were made to 1eV but the expected precision on the calculations from various calculational uncertainties is "usually" expected to be in the range of $\pm 5\text{eV}$ to $\pm 10\text{eV}$. This theoretical uncertainty is not due to imprecision in physical constants but rather to discrepancies in various computational schemes. The theoretical calculations are precise enough at the present time because the experimental uncertainty is always larger. In certain cases the experimental accuracy does approach $\pm 10\text{eV}$ but actually in these cases the magnitude of the theoretical uncertainties is smaller than the "usual" values.

The measured and calculated energies were compared for the ten targets from ${}^6\text{Li}$ to ${}^{17}\text{Yb}$. The mass of the antiproton was determined to be $938.229 \pm 0.049\text{MeV}$. Previous measurements had errors of ± 0.5 , ± 0.13 and ± 0.058 MeV with the last one differing from the mass of the proton by more than one standard deviation. The present measurement is within one standard deviation of the proton mass. The error on the proton mass is $\pm 0.0027\text{ MeV}$ which is 18 times smaller than the antiproton error.

The measurements of the effects of the antiproton-nucleus strong interaction determined level shifts and widths. The antiprotons cascade through the atomic states until they annihilate with the nucleons in the nucleus. The last observable x-ray transition places the antiproton in the highest n level in which the probability of nuclear absorption vastly dominates the probability of an electromagnetic transition, and contains the observable effects from the strong interaction on the energies, yields, and line widths.

Antiprotons in the upper state of the last transition are partially absorbed by the nucleus producing a reduction in the x-ray yield. The lower state may have an experimentally observable line broadening from the absorption and a shift in energy from the strong interaction. The higher transitions than the last one are almost unaffected by the strong interaction and were used to determine the antiproton mass.

A phenomenological fit to the data using an optical model potential proportional to the nuclear matter density and to an effective antiproton-nucleon s-wave scattering length yielded $((0.85 \pm 0.38) + i(2.66 \pm 0.28))$ fm for the effective scattering length. This result is useful to calculate the effects of the strong interaction for other nuclei and it is interesting that a single complex parameter will suffice for all nuclei. No evidence has been found yet in any shift, width, or yield measurements from $z = 3$ to $z = 92$ of any need for a more complicated form for the potential.

The 1s state measurements on H and He have just begun at BNL. We have made preliminary data collection runs on He gas, H gas, and H liquid to determine backgrounds and choose the most advantageous targets. The yields are very low for the desired x rays and the cryostat is made out of C, Al, and Fe which can produce x rays near the region of interest. The small high purity detectors have worked satisfactory and we have obtained some x-ray spectra to base future runs on. A group at CERN is attempting similar measurements but neither group has as yet produced convincing results.

During the reporting period, the principal investigator for Task B (R. Kunselman) devoted 85% of his time to this research.

PUBLICATIONS

- C00-2197-36 Atomic Structure Effects in Negative Meson Capture (Kunselman, Law, Leon, Miller), Phys. Rev. Lett. 36, 446 (1976).
- C00-2197-37 Excitation Functions of Reactions Induced by ^1H and ^2H Ions on Natural Mg, Al, Si, (Wilson, Detraz, Frantsvog, Kunselman, Zaidins), Phys. Rev. C 13, 976 (1976).
- C00-2197-38 Measurement of Kaonic X-Rays from Al, Si, Ni, and Cu (Barnes, Eisenstein, Lam, Miller, Sutton, Eckhause, Kane, Welsh, Jenkins, Kunselman, Powers, Redwine, Segal), Nucl. Phys. A231, 477 (1974).
- C00-2197-39 Negative-kaon mass, (Kunselman), Phys. Rev. C9, 2469 (1974) .
- C00-2197-40 Pionic 4f-3d transitions in ^{148}Nd and ^{150}Nd and the Neutron Isotope Shift, (Miller, Boehm, Powers, Zehnder, Kunselman, Roberson, Jarmer), Bul. Amer. Phys. Soc. 21, 586 (1976).
- C00-2197-41 Strong Interaction Effects in Kaonic and Pionic Atoms, (Roberts, Batty, Biagi, Blecher, Kunselman, Riddle, Davies, Pyle, Squier, Asbury, Hawkins), Bul. Amer. Phys. Soc. 21, 586 (1976).
- C00-2196-42 Muonic X-ray Study of the Charge Distribution of ^{165}Ho , (Powers, Boehm, Vogel, Zehnder, King, Kunselman, Roberson, Martin, Miller, Welsh, Jenkins), Nucl. Phys. A262, 493 (1976).
- C00-2197-43 Pion-nuclear Interactions and Mesonic Atoms, Progress Report, 1976, (Rebka, Kunselman).
- C00-2197-44 Pion-nuclear Interactions and Mesonic Atoms, Science Information Exchange 1976, (Rebka, Kunselman).