ABSTRACT

A STUDY OF ^{206}Pb BY INELASTIC SCATTERING OF 35 MeV PROTONS

By

Joseph Eugene Finck

Using high resolution techniques the inelastic scattering of 35 MeV protons by ^{206}Pb have been measured. A resolution of 6 to 9 keV allowed identification of approximately 180 levels of ^{206}Pb with excitation energies up to 6.8 MeV. Angular distributions of most of these states are measured. L-transfers and deformation parameters are determined by comparison of the measured angular distributions to collective model calculations. Strongly excited collective states are compared to analogous states in ^{207}Pb and ^{208}Pb and the overall distribution of inelastic strength in ^{206}Pb is compared to ^{208}Pb. Microscopic calculations of natural parity states are presented and allow a test of theoretical RPA and TDA wave functions. Unnatural parity states with well determined wave functions are also studied microscopically and permit an examination of the central and noncentral forces in the effective interaction.

A STUDY OF ^{206}Pb BY INELASTIC SCATTERING OF 35 MeV PROTONS

By

Joseph Eugene Finck

A DISSERTATION

Submitted to
Michigan State University
in parital fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Physics

1982

ACKNOWLEDGEMENTS

I would like to thank Professor G. M. Crawley for his constant guidance and assistance during the time that this work was performed. Professor J. S. Kovacs is also thanked for his support and understanding during my graduate career. Dr. J. A. Nolen, Jr. is thanked for his aid with this project and many helpful comments.

I would also like to recognize the staffs of the Michigan State Cyclotron Laboratory, Princeton Cyclotron Laboratory, and Northern Michigan University Physics Department. I am especially grateful for the aid and hospitality of Dr. R. Kouzes at Princeton and Dr. D. Fowler at Northern Michigan. Without these people this work would not have been possible.

Working with Bill Wagner, Rick Steele, and Paul Smith as a novice graduate student at the lab was an invaluable educational experience. In particular, my escapades with Paul will never be forgotten.

Bruce Hasselquist and Jim Duffy provided much companionship and support as officemates, especially during prelims together.

All my friends are thanked. In particular the members -- old and new -- of the Nuclear Beer Group. I am indebted to Reg Ronningen and Wayne Bentley for their

kindkness and comradery. Special thanks must be given to Jim Carr and Carol Dors for their close friendship. These individuals made my days as a graduate student most enjoyable and special.

I am grateful to the communities of Michigan State University and East Lansing for providing a nonpareil academic and pleasant social atmosphere for me to study and live in.

I owe a large debt to my parents for their support and prayers. To my wife, Deborah, I am grateful for her encouragement, understanding, and patience. Mostly, I am thankful for her love. My daughter, Elizabeth -- born during the preparation of Chapter IV of this thesis -- is recognized for her inspiration.

This thesis is dedicated to my entire family.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The lead region has always been an attractive area to test nuclear models. Nuclei in this mass region have been studied both experimentally and theoretically. The bulk of this work has involved the structure of the doubly-magic nucleus ^{208}Pb. Many of these studies have also extended to the single-hole structure of ^{207}Pb and the single-particle structure of ^{209}Bi which are now well-established. An examination of ^{206}Pb is a further step toward the more complex structure that exist away from closed shells.

Experiments previously performed on ^{206}Pb include inelastic scattering [Refs. I.1, I.2, and I.3] which has given information about the strongly excited states. Information about the microscopic structure of many of the low-lying states has been provided by decay studies [Refs. I.4, I.5, and I.6], transfer reactions [Refs. I.7, I.8, I.9, and I.10], and isobaric analog resonance experiments [Refs. I.11 and I.12]. The spins and parities of many higher-lying levels have also been determined by these experiments. Using the shell model which describes ^{206}Pb as two neutron holes in the ^{208}Pb core, energies and wave

functions of the low-lying levels of ^{206}Pb have been calculated [Refs. I.13 and I.14]. With this background a detailed study of inelastic proton scattering from ^{206}Pb, including collective and microscopic calculations, has been undertaken.

A direct reaction, such as inelastic proton scattering, can be used as a means to obtain spectroscopic information. In direct reaction experiments a beam of particles with a certain energy is focused on a target. The number of outgoing particles of a certain energy as a function of the angle between the incoming beam and the outgoing particles (the angular distribution) is measured. From these data the energy of the levels of the investigated nucleus can be directly determined; information about the spin and parity of the excited levels, and the spectroscopic strength for the excitation of these levels can be obtained by comparing the measured angular distributions with calculations assuming a specific configuration for the level considered.

Of all the direct reactions available proton scattering is the most appealing reaction to investigate nuclear structure and interactions. Almost all levels in a nucleus can be excited by means of inelastic scattering of protons with a beam energy for above the Coulomb barrier. However, the cross sections can be low. The structure of the states can be determined from comparison of the

experimental angular distribution for the level with that obtained from macroscopic or microscopic distorted wave calculations. When there are accurate wave functions available from model calculations microscopic calculations are preferred because these provide a better check on the proposed structure of the state. As the shape of angular distributions at forward angles and the magnitude of the overall angular distribution are very sensitive to the different configurations in the wave functions of the state, microscopic calculations are a suitable test for the wave functions.

The possibility of finding states which have not been seen before, together with the possibility of comparing the experimental angular distributions of the states with model calculations provide the motivation for a high resolution (p, p') experiment on ^{206}Pb.

A proton inelastic scattering experiment on ^{206}Pb has been reported [Refs. I.1, I.2, and I.3] at 24.5 MeV bombarding energy with an energy resolution of approximately 25 keV. This experiment identified 30 levels, and spin and parity assignments for the most strongly excited states were made. Using a collective model calculation, the reduced transition rates for some of these states were extracted. In this experiment, the angular distributions were compared only with the collective model predictions. The theoretical tools for a microscopic analysis were not

well developed at the time that this experiment was done. Furthermore, only states below 4.6 MeV of excitation energy were observed and in this region states weakly excited were not extracted. In addition, the resolution limited the number of states that could be analyzed unambiguously. This represents the most extensive study of ^{206}Pb (p, p') to date.

With the availability of particle accelerators with increased intensity and improved resolution, along with advances in magnetic spectrographs and particle detection devices, weakly excited levels and close lying excited levels can be resolved and studied. The microscopic description of nucleon-nucleus scattering has also progressed. Now with a better understanding of exchange effects and the nucleon-nucleon interaction, microscopic inelastic reaction theory can be used to study nuclear properties [Ref. I.15].

This thesis reports a study of ^{206}Pb (p, p') performed at 35 MeV with an energy resolution of 6 to 9 keV. Experimental procedures are described in Chapter II. Approximately 180 levels of ^{206}Pb with excitation energies up to 6.8 MeV are observed. Measured distributions for 144 of these levels are displayed. In Chapter III these results of the experiment are presented.

In the remaining chapters the theoretical models are compared with experimental results. The collective

model is used in fitting many of the measured angular distributions, and L-assignments and deformation parameters are obtained for these states. Systematics of strongly excited collective states in ^{206}Pb, ^{207}Pb, and ^{208}Pb are examined, and inelastic strengths of ^{206}Pb and ^{208}Pb are compared. Microscopic calculations are performed for a number of natural and unnatural parity states. The microscopic examination of natural parity states permits the testing of wave functions since such transactions depend little on the noncentral two-body interaction. Wave functions obtained from the random phase and Tamm-Dancoff approximations are examined. Unnatural parity transitions to levels with well determined wave functions allow the two-body central, tensor, and spin-orbit forces to be studied. In this study two different sets of forces are employed for comparison with experimental results.

In Appendix I, the methods used in the analysis of the data are outlined. This includes a description of the computer programs used to perform data reduction, determine excitation energies, extract angular distributions, and plot the results. Appendix II give examples of input to the distorted wave programs used in this study. Measured angular distributions of ^{206}Pb (p, p') are tabulated in Appendix III. Appendix IV lists abstracts of published papers to which I have contributed while a student at Michigan State University.

REFERENCES FOR CHAPTER I

I.1 J. Saundinos, G. Vallois, and O. Beer, Nucl. Sci. Appl. 3 (1967), 22.

I.2 G. Vallois, J. Saudinos, and O. Beer, Phys. Lett. 24B (1967), 512.

I.3 G. Vallois, Centre d'Etudes Nucleaives de Saclay, Report CEA-R-3500 (1968).

I.4 J. C. Manthuruthil, D. C. Camp, A. V. Ramayya, J. H. Hamilton, J. J. Pinajian, and J. W. Doornebos, Phys. Rev. C 6 (1972), 1870.

I.5 J. E. Draper, R. J. McDonald, and N. S. P. King, Phys. Rev. C 16 (1977), 1594.

I.6 D. F. Coope, L. F. Cannell, and M. K. Brussel, Phys. Rev. C 15 (1977), 1977.

I.7 W. A. Lanford, PHys. Rev. C 16 (1977), 988.

I.8 W. A. Lnaford and G. M. Crawley, Phys. Rev. C 9 (1974), 646.

I.9 R. Tickle and J. Bardwick, Phys. Rev. 166 (1968), 1167.

I.10 E. R. Flynn, R. A. Broglia, R. Liotta, and B. S. Nilsson, Nucl. Phys. A221 (1974), 509.

I.11 J. Solf, C. F. Moore, E. Grosse, and P. von Brentano, Nucl. Phys. A139 (1969), 523.

I.12 P. Richard, N. Stein, C. D. Kavaloski, and J. S. Lilley, Phys. Rev. 171 (1968), 1308.

I.13 W. W. True and C. W. Ma, Phys. Rev. C 3 (1971), 2421.

I.14 J. Vary and J. N. Ginocchio, Nucl. Phys. A166 (1971), 479.

I.15 G. R. Satchler, Comm. Nucl. and Part. Phys. 5 (1972), 39.

CHAPTER II

EXPERIMENTAL PROCEDURE

The experiment was performed using 35 MeV proton beams from the Michigan State University and Princeton University sector-focused cyclotrons. The Michigan State cyclotron delivered a proton beam of between 500- and 1500-nA average current on target. The average current from the Princeton cyclotron was between 50- and 150-nA.

Throughout the experiment ^{206}Pb targets of about 0.1 mg/cm^2 thickness were used. The targets were prepared by vacuum evaporation of the isotope, enriched to 97.22%, on a 20 $\mu g/cm^2$ carbon foil with a support of two layers of formvar. This choice of target thickness was based on a study by Wagner [Ref. II.1] which showed that lead targets of this thickness affect the resolution very little. In addition, targets of this thickness yield tolerable count rates, and skewing of peak shapes due to straggling of the protons in the target was reduced.

The beam on target was monitored by measuring the total charge collected in the Faraday cup and by measuring the number of beam particles elastically scattered into a NaI(TI) detector placed at an angle of 90° relative to the incident beam. This angle was chosen because 90° lies

near a relative maximum of the elastic cross section for ^{206}Pb and also gives a good separation of protons elastically scattered from lead and light mass contaminants in the target. The relative normalization obtained by these two measurements agree to within 5%.

The spectra from the part of the experiment at Michigan State were obtained using nuclear emulsions in the focal plane of the Enge split-pole magnetic spectrograph. This plate data was taken with a 0.6 milisteradian (1° x 2°) solid angle at forward angles and a 1.2 milisteradian (2° x 2°) solid angle at backward angles. A stainless steel absorber of thickness 0.25 mm was placed immediately before 20 inch Kodak NTB 25 μm nuclear emulsions. The absorber stopped all particles other than protons, and decreased the proton energy. This enhanced the proton tracks in the emulsion and did not significantly broaden the line width. On-line determination of the focal plane line width was optimized by adjusting the dispersion of the beam across the target using a "speculator" technique [Ref. II.2]. Once the dispersion was optimized, the resolution remained constant throughout the experiment. The resolution of the plate data ranges from 6-9 keV (FWHM). Each plate run covers a range of excitation energies from the ground state to about 7.0 MeV.

A typical spectrum of plate data is shown in Figure II.1. States of well-determined spin and parity have been

Figure II.1

Typical spectrum of protons scattered by ^{206}Pb obtained with a photographic plate. States of well-determined spin and parity are identified. The resolution is about 6 keV.