STUDY OF STRUCTURE OF LIGHT NUCLEI
WITH NEUTRONS

Progress Report

Raymond O. Lane

Ohio University
Athens, Ohio

September 1, 1975 - August 30, 1976

PREPARED FOR THE U. S. ENERGY RESEARCH AND DEVELOPMENT
ADMINISTRATION UNDER CONTRACT E(11-1)-2490

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ABSTRACT

The differential cross sections have been measured for neutrons scattered elastically at nine angles from several light nuclei for $4 \text{ MeV} \leq E_n \leq 8 \text{ MeV}$. These include ^6Li and ^7Li at 14 energies, ^{10}B at 30 energies, ^{11}B at 60 energies and ^{12}C at 3 energies. Inelastic scattering from ^7Li was also measured. Corrections to the data for multiple scattering and other effects are nearly completed. The data are being analyzed in terms of R-Matrix calculations with the aim of determining theoretical model properties of the compound systems. This comprehensive set of data together with the results of the analysis provides information of interest and use to the fission and fusion reactor programs where previously data were very sparse or nonexistent. Measurements and R-Matrix results will be correlated with evaluation groups working on ^6Li , ^{10}B and ^{12}C as standards for cross sections and flux measurements.

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I. INTRODUCTION

During this second year of this contract a large amount of elastic scattering data on ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^{10}\text{B}$, ${}^{11}\text{B}$ and ${}^{12}\text{C}$ have been obtained for neutron energies $4 \text{ MeV} \leq E_n \leq 8 \text{ MeV}$.

For most of these nuclei there existed previously virtually no data in this region whatever, or at best only a very few old measurements. These light nuclei are important components of both the fission reactor and fusion reactor designs. Our measurements reported here for the complete angular distributions of differential scattering cross sections at more than 14 energies for ${}^6\text{Li}$, 14 energies for ${}^7\text{Li}$, 30 energies for ${}^{10}\text{B}$, 60 energies for ${}^{11}\text{B}$ and several for ${}^{12}\text{C}$ provide a comprehensive data bank for the nuclear energy program. Our versatile on-line computer system and new time-of-flight spectrometer system have made it possible to perform these extensive experiments and have cross sections ready for theoretical analysis so soon.

Multiple scattering corrections are costly and time-consuming if done correctly, and are a vital and inescapable part of any serious neutron program. We have adapted to our needs A.B. Smith's program, Monte Sample, by rewriting it for our IBM 360/44 such that it was made faster by a factor of at least 5. This has allowed us to have by this time the majority of the data corrected for multiple scattering, with the remainder to be completed shortly.

With increased interest recently in the uses of ${}^6\text{Li}$ and ${}^7\text{Li}$ in the fusion reactor program we moved these measurements up on the priority list and performed the elastic and some inelastic scattering on these nuclei. The differential cross sections for the inelastic scattering from the first excited state of ${}^7\text{Li}$ (0.478 MeV) is very difficult to separate from the elastic and consequently there exists virtually no reliable data on this for $4 \text{ MeV} \leq E_n \leq 8 \text{ MeV}$. While the inelastic scattering for ${}^7\text{Li}$ is of interest for its own sake, it is also

related to the tritium breeding reaction ${}^7\text{Li} (n, n'\alpha) \text{T}$ in a blanket of a fusion reactor. Preliminary results for the elastic and inelastic cross sections for ${}^7\text{Li}$ are described in the report. The importance of ${}^6\text{Li}$ as a standard for cross sections and flux measurement is well known, and the recent work of G. Hale at LASL on the R-Matrix analysis of ${}^6\text{Li} + n$ was just reported at the Lowell Conference (1976 International Conference on Interactions of Neutrons with Nuclei, July 6-9, 1976). This analysis which extends into our energy region is to be continued up higher in energy so our data will form an important basis for these LASL fitting calculations since previously there existed very few data of any kind at these energies.

Our results in ${}^{10}\text{B}$ will also form a vital basis for the R-matrix calculations by Hale at LASL on the evaluation for ${}^{10}\text{B}$ for standards work. These calculations require for accuracy the knowledge of broad high energy states which appear in our data. Previous to this, there was essentially no data at these energies.

The results on ${}^{11}\text{B}$ are being investigated now for particle-hole structure in ${}^{12}\text{B}$ by R-matrix calculations under development here at Ohio University. This is a very interesting nucleus from the structure point of view and offers a good possibility to test the validity of the shell model when extended to high energies, including some continuum-shell-model calculations already made for ${}^{11}\text{B} + n$ leading to states in ${}^{12}\text{B}$.

II. Research Activities

A. Differential Cross Section Measurements

The differential cross sections for neutrons scattered from ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^{10}\text{B}$ and ${}^{11}\text{B}$ have been measured at 9 angles for an extensive set of incident energies between 4 MeV and 8 MeV. The first of the two following subsections describes the methods used for these measurements including experimental design, data reduction programs, multiple scattering corrections, and the system performance. The second subsection summarizes the data obtained on each of the nuclei above and includes plots of the differential cross sections for all nuclei studied.

1. Experimental Considerations (R. White, J. Cox, H. Knox, R. Lane)

a. Experimental Design

A neutron T.O.F. spectrometer with associated support system has been developed for rapid measurements and data reduction of neutron elastic differential cross sections with particular emphasis on light nuclei, e.g., $7 \leq A \leq 12$. Peculiar to these nuclei is the problem of energy loss of the elastically scattered neutrons due to the kinematics of scattering off very light scatterers. For example, a 4.00 MeV neutron incident on ${}^6\text{Li}$ will have only 2.07 MeV of energy after elastically scattering 160° . Therefore, a larger dynamic range of neutron energies is encountered at various spectrometer angles even for a small range of incident neutron energies. If the neutron detector system is to be biased such that the lowest energy neutrons are detected with good efficiency a well-shielded detector is necessary. Further, if data are to be acquired at a reasonably rapid rate a high current machine coupled to a prolific source of monoenergetic neutrons, a neutron detector of large solid angle, and larger size scattering sample are desirable. However, the larger sample size then requires that accurate codes exist to correct for finite sample size effects. To these ends the Ohio University neutron T.O.F. spectrometer and data reduction system have been developed.

Neutrons are provided by a pulsed proton beam of approximately 4.5 μ amps, 0.8 ns width and 5 MHz repetition rate incident upon a tritium gas cell designed by J. D. Carlson ¹⁾. The $T(p,n)^3\text{He}$ reaction provides a prolific monoenergetic source of neutrons to well beyond 8 MeV with a gas cell pressure of 18 psi. This pressure introduces an energy spread of ± 20 to ± 40 keV in the neutron burst. Scattering samples are cylindrical in shape with sizes approximately 4 cm high by 3.4 cm diameter and are isotopically enriched for ^6Li , ^{10}B and ^{11}B .

The neutron detector is NE 224 liquid scintillator housed in a 5 cm thick x 18 cm diameter lucite container optically coupled to an RCA 4522 PMT. The detector shield shown in Figure 1 consists of 8 inch I.D. 1 inch thick steel pipe around which is a 3 inch thick lead annulus 30 inches long in the region of the scintillator and a 2 inch thick lead annulus 24 inches long extending forward along the pipe. This represents over 1000 pounds of steel and 2000 pounds of lead shielding. Placed around the lead is 1750 pounds of steel shot and outside of that 1000 pounds of paraffin (above 5 MeV the inelastic scattering of neutrons by iron allows it to compare well with hydrogen as neutron shielding material). The total weight of the system neglecting the massive copper shadow bar and support is over 7000 pounds. Use of an air pad system allows movement of the shield by one person. The massive copper shadow bar can be repositioned accurately for different scattering angles and allows wide collimation to the sample. Data are normally taken at nine angles from 20° to 160° and at a neutron flight path of 3.6 meters.

b. Data Reduction Program

One of the most difficult problems in obtaining accurate results from angular distribution measurements is in determining the absolute efficiency of the neutron detector. For the energy range of interest in the present measurements a method has been developed which involves a relative efficiency determination and use of the well-known zero-degree cross sections ²⁾ (absolute yields)

Figure 1. The time-of-flight spectrometer.

for the $T(p,n)^3\text{He}$ reaction. These absolute cross sections are known to 2-1/2% and the data reduction program for this experiment utilizes only ratios, i.e., $\sigma(0^\circ, E_p')/\sigma(0^\circ, E_p)$ of these yields which really involves only the relative shape of the curve and that is known to an even better degree. For optimum results in terms of electronic bias settings, voltage ranges of equipment, etc., the measurements are usually carried out in three energy ranges between 4.0 and 8.0 MeV. A relative efficiency run is made for each energy range with the detector at 0° and the monitor at an angle of 25° . The relative efficiency runs use charge normalization which have been demonstrated to have an accuracy of 1%. The scattering data are taken with monitor left in its original position at 25° and the detector moved around to the various angles of scattering measurement with the scattered counts normalized to the monitor counts. The final formula for cross section involves integrated detector and monitor counts, ratios of zero degree cross sections for the $T(p,n)^3\text{He}$ reaction, and ratios of relative efficiency measurements for monitor and detector. Thus this method is equivalent to the placing of the detector in the direct beam to determine the flux incident on the scatterer.

The use of a reasonably simple program for reduction of counts to absolute cross section lends itself nicely to a fully automated data reduction system. The neutron T.O.F. spectra for both detector and monitor are accumulated in a MCA and transferred to disk on the laboratory's IBM 1800 computer. A panel of switches allows introduction of various experimental parameters--for example, the accelerator NMR freq., tritium gas cell pressure, run length in accumulated charge, angle of scattering, sample measured, etc. The on-line data reduction program then calculates all kinematics, calls up relevant relative efficiency information, analyzes monitor and detector spectra for dead time corrections, etc., formulates a subtracted spectra (sample in-sample out), picks integration channels, makes various corrections for finite geometry, attenuation of incident flux, etc., and presents final cross sections in both lab and cm frames to the control room type-

writer in a few seconds. Further, a CRT displays all spectrum analysis that the computer performs on a given energy-angle measurement for visual inspection by the investigator. A full computer log of information is printed on the various experimental parameters and all the above information is transferred to magnetic tape should further off-line data analysis be required. With this system a complete angular distribution can be taken in 4 to 12 hours, depending on the specific nucleus, with final cross sections obtained immediately. While rapid accumulation and reduction of data is desirable for many reasons, the most important benefit comes in allowing an investigator to stay completely on top of his experiment. Accuracy of the system is verified by measurement of certain well-known angular distributions on ^{12}C as described below and from integration of the elastic differential cross section below the inelastic threshold. The system was designed and maintains accuracy of measurements to within 5%.

c. Multiple Scattering Corrections

The multitude of problems normally existing with proper and accurate multiple scattering corrections are further complicated on very light nuclei because the energy of scattered neutrons may be considerably less due to kinematic shift and significant resonance structure may exist in the neutron cross section to be corrected. Further, the energy resolution of the T.O.F. system can change from forward to backward angles for a fixed flight path and fixed incident energy and multiple scattering corrections are, of course, sensitive to this energy resolution. In the data reduction program discussed above we have adopted A. B. Smith's Monte-Sample Multiple Scattering Code ³⁾ from ANL. The code has been extensively rewritten to speed up the long Monte-Carlo process and has been checked through more than 45 hours of IBM 360/44 computer time. Plots have been made from 500k to 3M histories vs. correction factors to assure convergence of the corrections per angle and many test cases run on this revised code.

The code will handle elastic and inelastic scattering and reactions, and takes as input information a total cross section library and an angular distribution library and therefore includes energy-dependence of differential cross sections of multiple events necessary for these very light nuclei. The code also employs an energy resolution quantity determined by the T.O.F. system as input information. The code as it has been rewritten at Ohio University runs approximately five times faster than the original Argonne code and while running times vary significantly with sample size, transmission, etc., the code will do on a sample of 80% transmission approximately one million histories in 45 minutes on an IBM 360/44 computer.

The multiple scattering corrections are then applied automatically to the angular distribution by the laboratory's IBM 1800 computer and finalized data cards are punched out for printing up tables of data for the various nuclei. As the multiple scattering corrections for three distributions can be run overnight, the finalized corrected data on a particular angular distribution can be made available within 24 hours of the measurement of the distribution.

d. System Performance

The accuracy of the entire experimental method is verified by measurements of certain well known differential cross sections on ^{12}C performed during the course of the experiment at energies spaced throughout the range of interest. Figure 2 shows a comparison of measurements of differential elastic scattering cross section $\sigma_{n_0}(\theta)$ for ^{12}C made at Ohio University (White, 1/76) with those at the University of Kentucky (Galati et al. ⁴⁾) and at ORNL (Perey et al. ⁵⁾) at three neutron energies. Remeasurements of these data two months later (Knox, 3/76) consistently agreed to within 2-3% in absolute value with earlier measurements. It should be noted here that the experimental methods and correction codes for each of the three laboratories were entirely different. The fact that the agreement is so good demonstrates the accuracy with which

Figure 2. Comparisons of $\sigma_{n_0}(\theta)$ data for ^{12}C . Where error bars are not shown they are smaller than the points.

these points can now be considered to be known. The relative ease and straightforward nature of these measurements compared to that of the often-used hydrogen should certainly establish these points as practical calibration standards for neutron work in this energy range on an equal footing with hydrogen.

2. Results and Discussions

a. ${}^6\text{Li} + n$ (H. Knox, R. White, R. Lane)

Figure 3 shows the Legendre polynomial expansion coefficients B_L of $\sigma_{n_0}(\theta)$ versus neutron energy for ${}^6\text{Li} + n$. Also shown are some representative angular distributions of $\sigma_{n_0}(\theta)$ throughout the energy range. In this figure and similar figures to follow, expansion coefficients, cross sections and angles are in the center-of-mass system while neutron energy is in the laboratory system. For ${}^6\text{Li} + n$, expansion coefficients greater than $L = 4$ were found to be negligible. The data shown here have been corrected for multiple scattering and isotope effects. For comparison with other measurements, Figure 4 shows plots of the present work (Knox et al.) together with those of LASL (Hopkins et al.⁶⁾) and Aldermaston (Batchelor et al.⁷⁾) at overlapping energies. Note the excellent agreement with Hopkins et al.⁶⁾. The data of Batchelor et al.⁷⁾ have not been corrected for multiple scattering, but typical corrections to their data would qualitatively move their points towards the present data. Figure 5 shows plots of the differential cross sections for neutrons scattered from ${}^6\text{Li}$ at all energies at which measurements were taken. In this figure and similar ones to follow, incident neutron energies are indicated adjacent to each distribution.

b. ${}^7\text{Li} + n$ (H. Knox, R. White, R. Lane)

For ${}^7\text{Li} + n$, neutrons inelastically scattered from the 478 keV level were never completely separated from the elastic group. Figure 6 shows a subtracted time-of-flight spectrum for 4.28 MeV neutrons scattered from ${}^7\text{Li}$ at 142.5° . At almost all angles, partial separation of the two peaks, as is the case here, was possible. These data were first analyzed by simply summing all

Figure 3. Coefficients B_L and some angular distributions of $\sigma_{n_0}(\theta)$ for ${}^6\text{Li} + n$.

Figure 4. Comparison of the present results with earlier LASL(Hopkins et al.) and Aldermaston(Batchelor et al.) work.

$6\text{Li} + \text{n}$

Figure 5. Differential cross sections, $\sigma_n(\theta)$, for neutrons scattered from ^6Li . Adjacent to each distribution is the incident neutron energy.

Figure 6. Subtracted time-of-flight spectrum for neutrons scattered from ${}^7\text{Li}$.

counts in the composite peak with no attempt to extract the inelastic group. The results are shown in Figure 7. Again plotted here are the Legendre expansion coefficients versus energy and some representative differential cross sections. Some structure is in evidence here --namely a broad resonance near 4.5 MeV, probably due to a level at 6.1 MeV excitation energy in ^8Li , and another narrower resonance near 6.5 MeV incident neutron energy. Figure 8 shows a comparison of the present results with those of Hopkins et al. ⁶⁾. Again the agreement is quite good. The differential cross sections for neutrons scattered from ^7Li at all energies at which measurements were made are shown in Figure 9.

Even though complete separation of the inelastic group was not possible, the inelastic cross section has subsequently been obtained by using curve fitting methods. In order to perfect the fitting procedure, the less complicated $^6\text{Li} + n$ data were first reanalyzed. Figure 10 shows a spectrum for 4.07 MeV neutrons scattered from ^6Li at 20° . In addition to the skewness towards the lower energy side of the peak, the presence of the minor ^7Li isotope complicates the fitting of these data. To account for the skewness, a function composed of the sum of two gaussians was assumed as the line shape. A similar shaped curve was assumed for the contribution of the ^7Li impurity. The position of the ^7Li peak was calculated from kinematics and its height was obtained from knowledge of the percentage of the minor isotope present in the sample. For each incident neutron energy, a function, having three variables--position, width and height of the elastic peak--was found by trial and error, which would fit data at all angles for that energy. Cross sections calculated using the areas under these curves agreed with cross sections calculated by simply summing counts in the peak to within 2%. Figure 10 shows the final fit to the data at this angle along with its decomposition into contributions of the elastic scattering from the ^6Li and the minor isotope.

In the $^7\text{Li} + n$ subtracted spectrum for 4.26 MeV incident neutron energy at 142.5° shown in Figure 6 there are three components--the elastic, the inelastic

Figure 7. Coefficients B_L and some angular distributions for $\sigma_{n_0+n_1}(\theta)$ for ${}^7\text{Li} + \text{n}$.

Figure 8. A comparison of the present results with earlier ${}^7\text{Li} + \text{n}$ measurements from LASL(Hopkins et al.).

${}^7\text{Li} + \text{N}$

ELASTIC + 0.478 MEV LEVEL

Figure 9. Differential cross sections, $\sigma_{n_0+n_1}(\theta)$, for neutrons scattered from ${}^7\text{Li}$. Incident neutron energies are indicated for each angular distribution.

Figure 10. Time-of-flight spectrum for neutrons scattered from ${}^6\text{Li}$. Solid curves are contributions from elastic scattering, minor isotope, and the sum of the two.

Figure 11. Composition of the final fit to the ${}^7\text{Li}$ data in Figure 6.

Figure 12. Final fit to ${}^7\text{Li} + \text{n}$ data at 142.5° and $E_n = 4.26 \text{ MeV}$.

Figure 13. Differential elastic and inelastic cross sections for ${}^7\text{Li} + \text{n}$.

and the minor isotope. In fitting these data, all three peaks were assumed to have the same basic shape as that found by fitting the ${}^6\text{Li}$ data at this energy. Figure 11 shows the fit to these data along with contributions of the elastic peak (on the right), the inelastic peak (on the left), and the minor isotope (in the middle). Four variables were used here, the position, height and width of the elastic peak and the height of the inelastic peak. The position of the inelastic peak was calculated from kinematics. Figure 12 shows the data again along with the final fit. Chi square for this fit is 1.2. From the parameters for the inelastic peak obtained in the fitting, one can calculate the inelastic cross section. For each incident neutron energy in these measurements, the inelastic cross section has been obtained for at least 8 of the 9 angles at which measurements were taken. The results of this fitting procedure are shown in Figure 13 for four incident neutron energies throughout the range of these measurements. Error bars are not shown on this figure if they are smaller than the symbols. For the inelastic cross sections errors are approximately 20% except at the most forward angles. At these forward angles, where the separation of the elastic and inelastic time-of-flight peaks is small and fitting the data is more difficult, the errors on the resulting cross sections are larger. In general, the inelastic cross section is nearly isotropic at the lower energies but is characterized by a negative B_2 Legendre expansion coefficient as the incident neutron energy increases. At the higher energies, the cross section at the backward angles is approximately one third that at 90° .

c. ${}^{10}\text{B} + n$ (R. White, H. Knox, R. Lane)

Figure 14 shows the B_L coefficients for the elastic differential scattering cross section $\sigma_{n_0}(\theta)$ for ${}^{10}\text{B}+n$ measured in this experiment from 4.0 MeV to 8.0 MeV along with a few representative angular distributions for $\sigma_{n_0}(\theta)$. Coefficients B_L for $L \geq 5$ are essentially zero and have not been plotted. The inelastic group for ${}^{10}\text{B}(n,n'){}^{10}\text{B}^*$ (0.717) was clearly resolved and separated off

Figure 14. Coefficients B_L and some angular distributions of $\sigma_n(\theta)$ for $^{10}\text{B} + n$.

below 7.5 MeV and corrections for it above this energy are now in progress. Figure 15 and 16 show plots of angular distributions for all the data. Multiple scattering corrections are being calculated and will be applied to these data shortly. Previously very few neutron scattering data existed in this energy range ⁸⁾. Earlier measurements ⁹⁾ of elastic scattering at our Laboratory extended up to 4.5 MeV and led to several assignments of states at lower energies including a tentative assignment for a resonance near $E_n \sim 4.2$ MeV of $(3/2, 5/2, 7/2)^+$ formed by d-waves. The present data are consistent with the earlier data in the overlap region and extend elastic measurements up into excitation energies of ^{11}B where little is known concerning the level structure. Resonance behavior that was only partially observed in the earlier work up to 4.5 MeV is now observed in its entirety up to ~ 5 MeV and may lead to a better determination of J^π for this state. Although the B_L here are slowly varying there does appear to be some broad and possibly composite structure between 6 MeV and 8 MeV. As the neutron energy rises toward 8 MeV the resonance structure practically disappears and the scattering may be going over the direct reaction as noted in the following section.

Since the nuclear data evaluation work at Los Alamos Scientific Laboratory on $^{10}\text{B}+n$ is to include data up to $E_n \sim 20$ MeV, these results will contribute information to a sizeable region of energy where practically no data existed previously. These results are needed by evaluators such as G. Hale (LASL) in order to determine properties of broad higher energy states which contribute to the cross sections at lower energies where ^{10}B is used as a standard.

An extension of our earlier R-matrix work at lower energies is being considered and would include the region of $4 \text{ MeV} \leq E_n \leq 8 \text{ MeV}$ of our new data reported here.

d. $^{11}\text{B}+n$ (R. White, J. Cox, H. Knox, R. Lane)

Elastic scattering results for $^{11}\text{B}+n$ are shown in Figure 17. Coefficients B_L for $L \geq 5$ are essentially zero and have not been plotted. Inelastic scattering was

$^{10}\text{B} + \text{N} \quad (1)$

Figure 15. Differential cross sections for neutrons scattered from ^{10}B .

Figure 16. Differential cross sections for neutrons scattered from ^{10}B .

Figure 17. Coefficients B_L and some angular distributions of $\sigma_{n_0}(\theta)$ for $^{11}\text{B} + n$.

completely separated and removed by time-of-flight. The pronounced resonance effects are especially apparent in the coefficients B_L for $1 \leq L \leq 4$ as compared with those of B_0 . On the right are plotted angular distributions at energies where variations are prominent.

The rapid growth of B_3 and especially B_4 above 4.5 MeV indicates, from angular momentum considerations, d-wave formation of negative-parity states of $J \geq 2$. Previous work at our Laboratory showed evidence ¹⁰⁾ for particle-hole structure at lower energies. Particle-hole shell-model calculations ¹¹⁾ in ^{12}C have in fact placed 2^- and 3^- $T=1$ states near an excitation energy of 23-24 MeV in ^{12}C which corresponds in ^{12}B to 5-6 MeV bombarding energy of neutrons on ^{11}B , which is just where strong resonance effects appear for B_3 and B_4 in Figure 17. Recent continuum shell-model calculations ¹²⁾ for neutron scattering from ^{11}B not only predict 2^- , 3^- and 4^- states in this same energy region but also calculate B_3 and B_4 coefficients with strong similarities to these data in their energy dependence. Notice the pronounced interference dip which occurs at 5.5 MeV in all five coefficients including B_0 . An interference dip in the integrated elastic scattering cross section σ_{el} ($= 4\pi B_0$) implies interference between two states of the same J^π . This unusual and very characteristic signature may aid in determining the assignments in this complex problem. Figures 18 through 21 show complete plots of all of the angular distributions for the data on ^{11}B .

At ~ 8 MeV a comparison of the angular distributions for $^{10}\text{B}+n$ and $^{11}\text{B}+n$ shows them to be very much alike. Further, since the total cross sections for ^{10}B and ^{11}B above this are practically smooth the scattering for both nuclei may be going over to direct reaction at the upper energies.

Previously there were very few neutron data available in this region of $4 \text{ MeV} \leq E_n \leq 8 \text{ MeV}$ other than total cross section. An extensive study ¹²⁾ of the reaction $^9\text{Be}(^7\text{Li}, \alpha)^{12}\text{B}$ has observed the presence of a large number of states in ^{12}B and shows very good agreement with neutron data in the region of overlap.

Figure 18. Differential cross sections for neutrons scattered from ^{11}B .

$^{11}\text{B} + \text{N}$ (2)

Figure 19. Differential cross sections for neutrons scattered from ^{11}B .

Figure 20. Differential cross sections for neutrons scattered from ^{11}B .

Figure 21. Differential cross sections for neutrons scattered from ^{11}B .

However, that work did not yield definite values of J^π for the states observed. So, there still remains little knowledge concerning the J^π of states for ^{12}B in the region of the present study.

The nucleus ^{12}N has been studied with some difficulty lately by the reaction $^{12}\text{C}(^3\text{He}, t)^{12}\text{N}$, however, while the existence of four new states was shown ¹⁴⁾, the level structure still remains very poorly known.

One of the primary goals of this work on $^{11}\text{B}+n$ is to extend the experimental knowledge of properties of states in ^{12}B to higher excitations for comparison with continuum shell-model calculations so that the model for the $A = 12$ system may be critically examined and hopefully improved. From a more complete understanding of the pure $T=1$ system of ^{12}B it is possible that by a suitable comparison of $T=1$ states some of the uncertainties of the ^{12}C system may be resolved, and further that more information on isospin mixing may be deduced.

An R-matrix analysis program to fit these data is currently being formulated to determine J^π and partial widths for states in ^{12}B corresponding to resonances in that data so that comparison with the theoretical predictions can be made.

B. Polarization Measurements (H. Knox, J. Cox, R. Lane)

Development of a well-shielded detector system for simultaneous measurement of neutron polarizations and differential cross sections is nearing completion. The $^9\text{Be}(p, \vec{n})^9\text{B}$ reaction will be used as a source of polarized neutrons in these experiments. A beryllium target system, which allows a maximum of shielding to be placed between the neutron producing target and the neutron detectors has been developed.

A spin precession magnet used previously at ANL and capable of precessing neutrons up to 4.2 MeV by 180° has been obtained for use in these measurements. The magnet has since been accurately calibrated by mapping its magnetic field with a Hall probe as a function of applied current. For neutron energies above

4.2 MeV polarization measurements will be made using partial precession of the neutron spins--the magnet is capable of precessing 6 MeV neutrons by 150° .

The neutron detectors are RCA 4522 photomultiplier tubes and each will have a 4.5 in diameter by 2 inch thick NE 213 scintillator bonded to it. Each detector is housed in a massive neutron shield that can be used for scattering angles between 30° and 130° . These wedgeshaped shields are each constructed of approximately 1000 pounds of paraffin and 1000 pounds of lead. The detector is located inside a long lead collimator approximately 2-1/2 inches thick which is in turn surrounded by paraffin. These shields afford excellent neutron and gamma ray shielding throughout the range of neutron energies of interest here. This consequent large reduction of background has allowed successful use of pulse shape discrimination techniques which further enhances signal-to-noise ratios. Currently work is underway to adequately shield the neutron detectors from the fringing fields of the spin precession magnet.

The completion of this system will give this laboratory a unique capability allowing the simultaneous measurement of neutron differential cross sections and polarizations in an energy range where these measurements are quite difficult and the data are sparse. The $A = 10$ system will first be studied via ${}^9\text{Be}(\vec{n},n){}^9\text{Be}$ and this will be followed by studies of the isotopes of lithium and boron.

C. Scientific Papers and Professional Activity

1. The Principal Investigator on this contract was invited to be Chairman of the Session PB1 of the 1976 Conference on Interactions of Neutrons with Nuclei, University of Lowell, Lowell, Massachusetts, July 6-9, 1976.

2. The following is an abstract of a paper presented at the Washington, D.C. Meeting of the American Physical Society, April 26-29, 1976:

Differential Cross Sections for 4.0 to 8.0 MeV Neutrons Scattered from

${}^{10}\text{B}$ and ${}^{11}\text{B}$.* R. M. White, J. M. Cox⁺, H. D. Knox, and R. O. Lane, Ohio

University. -- Neutrons produced by the $T(p,n)^3\text{He}$ reaction with the Ohio University Tandem Van de Graaff were scattered from enriched samples of ^{10}B (92.3%) and ^{11}B (97.2%). Nine angles were measured from 20° to 160° by time of flight methods with a 3.6 meter neutron flight path. Over 50 angular distributions for ^{11}B and 25 for ^{10}B were obtained at energies of 4.0 to 8.0 MeV where data are very scarce because these energies are not practical for neutron work on most accelerators. Results, corrected for attenuation, finite geometry, air scattering, and multiple scattering, show slowly varying cross sections in ^{10}B and little resonance structure. However, ^{11}B shows evidence of considerable interfering resonance structure above 5.0 MeV with large d-wave contributions.

* Work supported by ERDA.

+ Now at Owens-Corning, Granville, Ohio

3. The following is an abstract of a paper presented at the 1976 International Conference on Interactions of Neutrons with Nuclei, University of Lowell, Lowell, Massachusetts, July 6-9, 1976:

ELASTIC SCATTERING OF 4 TO 7.50 MEV NEUTRONS

FROM ^6Li AND ^7Li

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* Work Supported by U. S. ERDA

RESUME

The differential cross sections for neutrons having energies $4 \leq E_n \leq 7.50$ MeV elastically scattered from ^6Li and ^7Li have been measured. These results, which are of interest to the nuclear energy program, show steady progression to forward peaking with little evidence of resonance structure.

ABSTRACT

The differential cross sections of neutrons elastically scattered from ^6Li and ^7Li have been measured for incident neutron energies between 4 and 7.50 MeV at approximately 250 keV intervals. A pulsed proton beam, approximately 0.8 ns burst width, from the Ohio University tandem accelerator incident on a tritium gas cell provided the source of neutrons. The ^6Li scattering sample was enriched to 96% ^6Li , while the ^7Li sample was normal lithium having 92.6% ^7Li . Both metallic samples were encased in thin aluminum cans. Measurements were made at nine equally spaced laboratory angles between 20° and 160° , using time-of-flight methods. The neutron detector was a 5 cm thick by 18 cm diameter NE224 scintillator coupled to an RCA 4522 photomultiplier tube and was located 3.6 meters from the scatterer.

In the case of scattering from ${}^7\text{Li}$, it was possible at some angles to resolve neutrons inelastically scattered to the 0.478 MeV level in ${}^7\text{Li}$ from the elastically scattered neutrons. Corrections for attenuation, air scattering, isotopic abundance, finite geometry and multiple scattering have been made. The results show slowly varying cross sections with little resonance structure for both ${}^6\text{Li}$ and ${}^7\text{Li}$ in this energy range.

4. The following is an abstract of an invited Special Contribution paper presented at the 1976 International Conference on Interactions of Neutrons with Nuclei, University of Lowell, Lowell, Massachusetts, July 6-9, 1976. This paper has just been submitted for publication in the proceedings of this conference and the complete text appears at the end of this report.

STRUCTURE STUDIES OF ${}^7\text{Li}$, ${}^8\text{Li}$, ${}^{11}\text{B}$ AND ${}^{12}\text{B}$ FROM

ELASTIC SCATTERING OF NEUTRONS*

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*Work Supported by U. S. ERDA

RESUME

The differential elastic cross section for neutrons scattered from ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^{10}\text{B}$ and ${}^{11}\text{B}$ have been measured at 9 angles for an extensive set of incident energies between 4 MeV and 8 MeV. The analysis of these data via the R-matrix and other methods provides information on the structure such as particle-hole states in the compound nuclei.

ABSTRACT

The Ohio University tandem accelerator was employed to produce neutrons via the reaction $\text{T}(p,n){}^3\text{He}$ in the range $4\text{ MeV} \leq E_n \leq 8\text{ MeV}$ where only sparse scattering data exist for several of the light nuclei. Differential elastic scattering cross sections were measured in this range for ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^{10}\text{B}$ and ${}^{11}\text{B}$ at 9 angles from 20° to 160° with time-of-flight techniques for a flight path of 3.6 m. The tritium gas cell used for the source introduced an energy spread of $\pm 35\text{ keV}$. The detector was NE224 liquid scintillator of 5 cm thickness and 18 cm diameter housed in a large collimator-shield rotated on air pads. Multiple scattering corrections include energy-dependence of the differential cross sections of multiple events necessary for these very light nuclei.

The coefficients B_L of Legendre polynomial expansions of the differential cross sections for ^{10}B show broad resonance behavior near $E_n \sim 4.2$ MeV and 7.5 MeV. For the 30 energies at which angular distributions were measured on ^{10}B the B_L for $L \geq 5$ were negligible.

The strong resonance structure present in the B_L for ^{11}B is much narrower and shows considerable interference effects between states. Contributions by resonant d-waves are large as would be expected in this energy region which contains the parents of the $T = 1$ analog states in ^{12}C of the giant dipole resonance. Angular distributions for ^{11}B were measured at 60 energies between 4 MeV and 8 MeV and again B_L for $L \geq 5$ were negligible. From R-matrix analyses of the data, properties of these states will be extracted. This yields information on particle-hole structure of ^{12}B expected in this region and affords a comparison with model calculations in the $A = 12$ system.

III. Conclusions

During this second year of the contract progress in the performance under the contract was very good and has resulted in the measurement of a large amount of cross section data on the light nuclei ^6Li , ^7Li , ^{10}B , ^{11}B and ^{12}C which are of interest to the fission and fusion reactor programs and to the use of standards for cross sections and flux measurement. These experiments are long and difficult, yet this considerable amount of data was obtained with good accuracy by considerable effort despite the shortage of manpower caused by the mid-year departure of one postdoctorate to a permanent position in industry, and the reduced availability of more first-class graduate students in experimental neutron physics.

The analysis of the data reported here will be pursued for the remainder of the contract period both to supply the National Neutron Cross Section Center at BNL with the best possible data in this range for use in the nuclear energy program, as well as to study the structure of the compound nuclei ^7Li , ^8Li , ^{11}B , ^{12}B and ^{13}C . It will be noted that, although we can and will as the situation warrants measure cross sections accurately from approximately 0.1 MeV to 25 MeV, the current on-going programs at ANL (A. B. Smith) up to 4 MeV, Ohio University from 4 MeV to ~ 8 MeV, and Duke University from 8 to 15 MeV combine nicely to provide a full spectrum of data for the nuclear energy program.

Through the academic year, the principal investigator devoted 30% of his time to this project and during this summer is devoting 100% of his time to it. Further, in the coming fall quarter of the academic year the principal investigator will again devote 30% of his time to this contract.

IV. Scientific Staff

Post Doctorates: Harold D. Knox

John M. Cox (4 months)

Graduate Student: Roger M. White

V. REFERENCES

1. J. D. Carlson, Nucl. Instrum. Methods 113, 541 (1973).
2. H. Liskien and A. Paulsen, Nucl. Data Tables 11, 569 (1973); D. K. McDaniels, M. Drosig, J. C. Hopkins and J. D. Seagrave, Phys. Rev. C6, 1593 (1972) [see references in this article].
3. A. B. Smith, Argonne National Laboratory (private communication).
4. W. Galati, J. D. Brandenberger and J. L. Weil, Phys. Rev. C5, 1508 (1972).
5. F. G. Perey and W. E. Kinney, Oak Ridge National Laboratory Report No. ORNL-4441, 1969 (unpublished).
6. J. Hopkins and D. Drake, Nucl. Phys. A107, 139 (1968).
7. R. Batchelor and J. Towle, Nucl. Phys. 47, 385 (1963).
8. F. Ajzenberg-Selove, Nucl. Phys. A248, 1, 1975.
9. S. L. Hausladen, C. E. Nelson and R. O. Lane, Nucl. Phys. A217, 563 (1973); J. M. Cox, H. D. Knox, R. O. Lane and R. W. Finlay, Nucl. Phys. A203, 89 (1973).
10. C. E. Nelson, S. L. Hausladen and R. O. Lane, Nucl. Phys. A217, 546 (1973).
11. V. Gillet and N. Vinh Mau, Nucl. Phys. 54, 321 (1964); D. J. Rowe and S. S. M. Wong, Nucl. Phys. A153, 561 (1970).
12. J. Birkholz and V. Heil, Nucl. Phys. A225, 429 (1974); V. Heil, "Continuum Shell Model Calculation for Neutron Scattering from ^{11}B " (Diplomarbeit), Technische Hochschule Darmstadt, September, 1973.
13. F. Ajzenberg-Selove, R. Middleton and J. D. Garrett, Phys. Rev. C12, 1868 (1975).
14. C. F. Maguire, D. L. Hendrie, D. K. Scott, J. Mahoney and F. Ajzenberg-Selove, Phys. Rev. C13, 933 (1976).

APPENDIX

STRUCTURE STUDIES OF ${}^7\text{Li}$, ${}^8\text{Li}$, ${}^{11}\text{B}$ AND ${}^{12}\text{B}$ FROM
ELASTIC SCATTERING OF NEUTRONS*

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* Work supported by U. S. ERDA

INTRODUCTION AND EXPERIMENT

The rate of growth of our knowledge of the energy level structure in many of the very light nuclei has slowed down considerably in recent years. This is largely because of the increased difficulties experienced with the more common charged-particle experiments in unambiguously determining J^π and other properties at higher excitation energies. In several of these cases neutron elastic scattering measurements offer possibilities of determining more of the structure information so that theorists may be encouraged to extend model calculations up to higher excitations. There exist only sparse measurements at higher energies because neutron measurements here are not practical on most accelerators. Because of this and difficulties with charged-particle experiments little information exists at these energies on properties of states in the compound nuclei. The nuclear energy program, too, has an interest in cross section measurements for the light nuclei since several of these are used in fission and fusion reactors as well as in standards for measurement of neutron fluxes and cross sections.

Differential elastic scattering cross sections have been measured in this experiment for ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^{10}\text{B}$ and ${}^{11}\text{B}$ for neutron energies between 4 MeV and 8 MeV. The measurements were made at the Ohio University Accelerator Laboratory where the Tandem Van de Graaff was employed to produce neutrons via the zero-degree yield of the $\text{T}(p,n){}^3\text{He}$ reaction. The accelerator provided a pulsed and bunched beam of protons of approximately 4.5 μamps average current and 0.8 ns width at a repetition rate of 5 MHz which was incident upon a tritium gas cell designed by J. D. Carlson¹). The gas cell, approximately 3 cm in length and containing 18 psi of tritium, introduced a spread of 40 to 70 keV of energy to the neutron burst. The scattering samples used were contained in thin-walled aluminum cans and consisted of isotopically enriched ${}^6\text{Li}$ (96%), ${}^{10}\text{B}$ (92%), ${}^{11}\text{B}$ (97%) and natural lithium. The detector shield and collimator weigh over 7000 pounds and consist of several thousand pounds each of iron and lead and over 1000 pounds of paraffin and polyethylene shielding. A copper shadow bar can be repositioned accurately for different angular measurements and the use of an air pad system allows movement of the shield by one person. The neutron flight path for these measurements was 3.65 meters and angular distributions consisted of measurements at nine equally spaced angles from 20° to 160° .

The neutron detector was 2" thick by 8" diameter NE224 liquid scintillator housed in a lucite container optically coupled to an RCA 4522 photomultiplier. The monitor was a thin plastic scintillator coupled to an RCA 8575 photomultiplier. Standard time-of-flight (TOF) techniques were employed with pulse shape discrimination used on the detector.

To determine the absolute conversion of counts to cross section a method was developed which utilizes only the ratios of the well-known zero-degree cross section²⁾ for the $T(p,n)^3\text{He}$ reaction at one energy compared to that at another energy. For an initial calibration measurement the main detector was located at zero degrees and the monitor at 25° with respect to the incident protons. Measurements of counts at neutron energies to be covered in the experiment were charge-normalized with a very accurate current integrator system developed at our laboratory. With the monitor left in its position, the detector was moved to the various angles for data taking and detector counts were then normalized to the monitor.

The neutron TOF spectra for both detector and monitor were accumulated in a multichannel analyzer and transferred to disk on the laboratory's IBM 1800 computer. A panel of switches allowed introduction of various experimental parameters for each energy-angle measurement. The on-line data reduction program then makes all the necessary calculations and corrections except for multiple scattering and presents final cross sections to the control room in a few seconds. Further, a CRT displays all spectrum analysis that the computer performs on a given energy-angle measurement for visual inspection by the investigator.

Proper and accurate multiple scattering corrections for the very light nuclei are complicated by the considerable neutron energy shift upon scattering and the presence of strong resonance structure. Further, the energy resolution of the TOF system can change from forward to backward angles for a fixed flight path and multiple scattering corrections are sensitive to this resolution. Multiple scattering corrections to the data are being made utilizing a routine originally written by A. B. Smith³⁾ and rewritten at Ohio University to speed up by a factor of five the long Monte-Carlo process. This program includes energy-dependence of differential cross sections of multiple events as well as energy resolution of the TOF system, both of which are necessary for these very light nuclei.

Figure 1. Comparisons of $\sigma_{n0}(\theta)$ data for ^{12}C . Where error bars are not shown they are smaller than the points.

Figure 2. Coefficients B_L and some angular distributions of $\sigma_{n0}(\theta)$ for ${}^6\text{Li}+n$.

The accuracy of the entire experimental method is verified by measurements of certain well known differential cross sections on ^{12}C performed during the course of the experiment at energies spaced throughout the range of interest. Figure 1 shows a comparison of measurements of differential elastic scattering cross section $\sigma_{n0}(\theta)$ for ^{12}C made at Ohio University (White) with those at the University of Kentucky (Galati *et al.*⁴) and at ORNL (Perey *et al.*⁵) at three neutron energies. Remeasurements of these data two months later consistently agreed to within 2-3% in absolute value with earlier measurements. It should be noted here that the experimental methods and correction codes for each of the three laboratories were entirely different. The fact that the agreement is so good demonstrates the accuracy with which these points can now be considered to be known. The relative ease and straightforward nature of these measurements compared to that of the often-used hydrogen should certainly establish these points as practical calibration standards for neutron work in this energy range on an equal footing with hydrogen.

RESULTS AND DISCUSSION

$^6\text{Li}+n$:

Figure 2 shows the Legendre polynomial expansion coefficients B_L of $\sigma_{n0}(\theta)$ versus neutron energy for $^6\text{Li}+n$. Also shown are some representative angular distributions of $\sigma_{n0}(\theta)$ throughout the energy range. In this figure and similar

Figure 3. Comparison of the present results with earlier LASL (Hopkins *et al.*) and Aldermaston (Batchelor *et al.*) work.

figures to follow, expansion coefficients, cross sections and angles are in the center-of-mass system while neutron energy is in the laboratory system. For ${}^6\text{Li}+n$, expansion coefficients greater than $L = 4$ were found to be negligible. The data shown here have been corrected for multiple scattering and isotope effects. For comparison with other measurements, Figure 3 shows plots of the present work (Knox *et al.*) together with those of LASL (Hopkins *et al.*⁶⁾) and Aldermaston (Batchelor *et al.*⁷⁾) at overlapping energies. Note the excellent agreement with Hopkins *et al.* The data of Batchelor *et al.* have not been corrected for multiple scattering, but typical corrections to their data would qualitatively move their points towards the present data.

${}^7\text{Li}+n$:

For the same incident neutron energy range as the ${}^6\text{Li}+n$ measurements, differential cross sections for ${}^7\text{Li}+n$ have been obtained. A level diagram of the ${}^8\text{Li}$ system is shown in Figure 4 with arrows indicating the limits over which these data were obtained. Figure 5 shows the expansion coefficients B_L of the sum of the elastic and inelastic (0.478 MeV level) cross sections for ${}^7\text{Li}+n$ along with selected angular distributions. These data have been corrected for isotopic effects but not for multiple scattering. Though the coefficients in Figure 5 are slowly varying, some resonance structure is indicated--notably the peak in B_0 and B_2 around $E_n = 4.5$ MeV probably caused by the level at $E_x = 6.1$ MeV in ${}^8\text{Li}$ and a smaller peak near $E_n = 6.5$ MeV possibly caused by a level not indicated on Figure 4.

Throughout these measurements, the neutrons inelastically scattered to the 0.478 MeV level in ${}^7\text{Li}$ were never completely resolved from the elastically scattered group. At most angles, however, the two groups were partially resolved. By fitting the "uncontaminated" ${}^6\text{Li}$ spectrum one can obtain the shape of the time-of-flight peak for the elastically scattered neutrons. Assuming the same general shape for both the elastic and inelastic groups for the ${}^7\text{Li}$ measurements one can obtain both the elastic and inelastic cross sections. Work is currently underway on this fitting process.

Cross section measurements on ${}^6\text{Li}$ and ${}^7\text{Li}$ were reported earlier by Behren *et al.*⁹⁾ and Glendinning *et al.*¹⁰⁾ at Duke for $7 \leq E_n \leq 15$ MeV. Measurements between 2 and 4 MeV on these nuclei have been recently completed at Argonne¹¹⁾. The present measurements nicely fill the gap between the other measurements and

Figure 4. Level diagram of ${}^8\text{Li}$ from Reference 8.

Figure 5. Coefficients B_L and some angular distributions for $\sigma_{n_0+n_1}(\theta)$ for ${}^7\text{Li}+\text{n}$.

Figure 6. Coefficients B_L and some angular distributions of $\sigma_{n0}(\theta)$ for $^{10}\text{B} + \text{n}$.

the three combined give accurate cross sections for both isotopes up to $E_n = 15$ MeV which will be of considerable value to the CTR program.

$^{10}\text{B}+n$:

Figure 6 shows the B_L coefficients for the elastic differential scattering cross section $\sigma_{n0}(\theta)$ for $^{10}\text{B}+n$ measured in this experiment from 4.0 MeV to 8.0 MeV along with a few representative angular distributions for $\sigma_{n0}(\theta)$. Coefficients B_L for $L \geq 5$ are essentially zero and have not been plotted. The inelastic group for $^{10}\text{B}(n,n')^{10}\text{B}^*$ (0.717) was clearly resolved and separated off below ~ 7.5 MeV and corrections for it will be made above this. Multiple scattering corrections are being calculated and will be applied to these data shortly. Previously very few neutron scattering data existed in this energy range. Earlier measurements¹²⁾ of elastic scattering at our Laboratory extended up to 4.5 MeV and led to several assignments of states at lower energies including a tentative assignment for a resonance near $E_n \sim 4.2$ MeV ($E_x \sim 15.3$ MeV) of $(3/2, 5/2, 7/2)^+$ formed by d-waves. The present data are consistent with the earlier data in the overlap region and extend elastic measurements up into excitation energies of ^{11}B where little is known concerning the level structure. Resonance behavior that was only partially observed in the earlier work up to 4.5 MeV is now observed in its entirety up to ~ 5 MeV and may lead to a better determination of J^π for this state. Although the B_L here are slowly varying there does appear to be some broad and possibly composite structure between 6 MeV and 8 MeV.

Figure 7. Partial energy level diagram for ^{11}B from Reference 13.

Figure 8. Coefficients B_L and some angular distributions of $\sigma_{n0}(\theta)$ for $^{11}\text{B}+\text{n}$.

In Figure 7 the heavy arrows on the partial energy level diagram of ^{11}B indicate the energy range of this experiment. The assignment $(3/2, 5/2, 7/2)^+$ from our earlier elastic scattering work for a state near $E_x \sim 15.3$ MeV ($E_n \sim 4.2$ MeV) is shown as added to the diagram of Reference 13 and would be $T=1/2$. At nearly the same excitation energy a $T=3/2$ state was observed¹⁴⁾ as a broad resonance in the $^{10}\text{Be}(p, \gamma_0)^{11}\text{B}$ reaction, but no J^π assignments were made. Although the lower part (below $E_x \sim 20$ MeV) of the giant dipole resonance in ^{11}B is reported¹⁵⁾ to be mainly $T=1/2$ and the upper part mainly $T=3/2$, a study of the present data and all other data in this high excitation region may lead to a better understanding of isospin mixing in this region. A program of R-matrix analysis of the elastic scattering data is being contemplated in order to better determine properties of states between 15 MeV and 19 MeV where little is presently known.

As the neutron energy rises toward 8 MeV the resonance structure practically disappears and the scattering may be going over the direct reaction as noted in the following section.

Since the nuclear data evaluation work at Los Alamos Scientific Laboratory on $^{10}\text{B}+n$ is to include data up to $E_n \sim 20$ MeV, these results will contribute information to a sizeable region of energy where very few data existed previously.

$^{11}\text{B}+n$:

Elastic scattering results for $^{11}\text{B}+n$ are shown in Figure 8. Coefficients B_L for $L \geq 5$ are essentially zero and have not been plotted. Inelastic scattering was completely separated and removed by time-of-flight. The pronounced resonance effects are especially apparent in the coefficients B_L for $1 \leq L \leq 4$ as compared with those of B_0 . On the right are plotted angular distributions at energies where variations are prominent. Multiple scattering calculations have just been completed for this nucleus but have not yet been applied to the data shown.

The rapid growth of B_3 and especially B_4 above 4.5 MeV indicates, from angular momentum considerations, d-wave formation of negative-parity states of $J \geq 2$. Previous work at our Laboratory showed evidence¹⁶⁾ for particle-hole structure at lower energies. Particle-hole shell-model calculations¹⁷⁾ in ^{12}C have in fact placed 2^- and 3^- $T=1$ states near 23-24 MeV which corresponds in ^{12}B to 5-6 MeV bombarding energy of neutrons on ^{11}B , which is just where strong resonance effects appear for B_3 and B_4 in Figure 8. Recent continuum shell-

Figure 9. Energy level diagram of ^{12}B from Reference 7.

Figure 10. Partial energy level diagram for ^{12}C from Reference 7.

model calculations¹⁸⁾ for neutron scattering from ^{11}B not only predict 2^- , 3^- and 4^- states in this same energy region but also calculate B_3 and B_4 coefficients with strong similarities to these data in their energy dependence.

An R-matrix calculation to fit these data is currently being formulated to determine J^π and partial widths for states in ^{12}B corresponding to resonances in the data so that comparison with the theoretical predictions can be made. Notice the pronounced interference dip which occurs at 5.5 MeV in all five coefficients including B_0 . An interference dip in the integrated elastic scattering cross section $\sigma_{el} (= 4\pi B_0)$ implies interference between two states of the same J^π . This unusual and very characteristic signature may aid in sorting out assignments in this complex problem.

Figure 11. Partial energy level diagram for the A = 12 system from Reference 7 showing the known T=1 states.

At ~ 8 MeV a comparison of the angular distributions for $^{10}\text{B}+n$ and $^{11}\text{B}+n$ from Figures 6 and 8 shows them to be very much alike. Further, since the total cross sections for ^{10}B and ^{11}B above this are practically smooth (Figures 7 and 9) the scattering for both nuclei may be going over to direct reaction at the upper energies.

In Figure 9 the heavy arrows indicate the energy range of this experiment in ^{12}B . Previously there were very few neutron data available in this region other

than total cross section. An extensive study¹⁹⁾ of the reaction ${}^9\text{Be}({}^7\text{Li}, \alpha){}^{12}\text{B}$ has observed the presence of a large number of states in ${}^{12}\text{B}$ and shows very good agreement with neutron data in the region of overlap. However, there still remains little knowledge concerning the J^π of states for ${}^{12}\text{B}$ in the region of the present study. The heavy arrows in Figure 10 indicate the corresponding excitation energy interval in ${}^{12}\text{C}$ where many of the $T=1$ assignments are tentative. These states are often observed as small peaks on a larger envelope, such as the data for the ${}^{11}\text{B}(p, \gamma_0){}^{12}\text{C}$ and other reactions shown on the right of Figure 10. Several of these results are from reactions which are sensitive primarily to 1^- states forming part of the strength of the giant dipole resonance. Figure 11 shows a partial level diagram of the $A = 12$ system. The heavy dashed lines connect the region of study in ${}^{12}\text{B}$ with the corresponding interval in ${}^{12}\text{C}$. The nucleus ${}^{12}\text{N}$ has been studied with some difficulty lately by the reaction ${}^{12}\text{C}({}^3\text{He}, t){}^{12}\text{N}$, however, while the existence of four new states was shown²⁰⁾, the level structure still remains very poorly known.

One of the primary goals of this work on ${}^{11}\text{B}+n$ is to extend the experimental knowledge of properties of states in ${}^{12}\text{B}$ to higher excitations for comparison with continuum shell-model calculations so that the model may be critically examined and hopefully improved. From a more complete understanding of the pure $T=1$ system of ${}^{12}\text{B}$ it is possible that by a suitable comparison of $T=1$ states some of the uncertainties of the ${}^{12}\text{C}$ system may be resolved, and further that more information on isospin mixing may be deduced.

REFERENCES

1. J. D. Carlson, Nucl. Instrum. Methods 113, 541 (1973).
2. H. Liskien and A. Paulsen, Nucl. Data Tables 11, 569 (1973); D. K. McDaniels, M. Drosch, J. C. Hopkins and J. D. Seagrave, Phys. Rev. C6, 1593 (1972) [see references in this article].
3. A. B. Smith, Argonne National Laboratory (private communication).
4. W. Galati, J. D. Brandenberger and J. L. Weil, Phys. Rev. C5, 1508 (1972).
5. F. G. Perey and W. E. Kinney, Oak Ridge National Laboratory Report No. ORNL-4441, 1969 (unpublished).
6. J. Hopkins and D. Drake, Nucl. Phys. A107, 139 (1968).
7. R. Batchelor and J. Towle, Nucl. Phys. 47, 385 (1963).
8. F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. A227, 1 (1974).
9. P. Behren, F. Purser, C. Gould, D. Glasgow, P. Lisowski, H. Hogue, S. Glendinning, W. Tornow, L. Seagondollar, D. Epperson, C. Nelson, J. Joyce and H. Newson, Bull. Am. Phys. Soc. 21, 1 (1976).
10. S. Glendinning, P. Lisowski, H. Hogue, W. Tornow, D. Epperson, C. Nelson, P. Von Behren, H. Newson and F. Purser, Bull. Am. Phys. Soc. 21, 536 (1976).
11. A. B. Smith, Argonne National Laboratory (private communication).
12. S. L. Hausladen, C. E. Nelson and R. O. Lane, Nucl. Phys. A217, 563 (1973); J. M. Cox, H. D. Knox, R. O. Lane and R. W. Finlay, Nucl. Phys. A203, 89 (1973).

13. F. Ajzenberg-Selove, Nucl. Phys. A248, 1 (1975).
14. D. R. Goosman, E. G. Adelberger and K. A. Snover, Phys. Rev. C1, 123 (1970).
15. B. H. Patrick, H. A. Medicus, G. K. Mehta, E. M. Bowey and D. B. Gaythers, Phys. Lett. 34B, 488 (1971).
16. C. E. Nelson, S. L. Hausladen and R. O. Lane, Nucl. Phys. A217, 546 (1973).
17. V. Gillet and N. Vinh Mau, Nucl. Phys. 54, 321 (1964); D. J. Rowe and S. S. M. Wong, Nucl. Phys. A153, 561 (1970).
18. J. Birkholz and V. Heil, Nucl. Phys. A225, 429 (1974); V. Heil, "Continuum Shell Model Calculation for Neutron Scattering from ^{11}B " (Diplomarbeit), Technische Hochschule Darmstadt, September, 1973.
19. F. Ajzenberg-Selove, R. Middleton and J. D. Garrett, Phys. Rev. C12, 1868 (1975).
20. C. F. Maguire, D. L. Hendrie, D. K. Scott, J. Mahoney and F. Ajzenberg-Selove, Phys. Rev. C13, 933 (1976).