STUDY OF STRUCTURE OF NUCLEI WITH NEUTRONS
and
NUCLEAR DATA MEASUREMENTS FOR MFE

Progress Report

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ABSTRACT

Measurements of neutron differential elastic and inelastic scattering cross sections have been made for ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^{11}\text{B}$ and ${}^{13}\text{C}$. For ${}^7\text{Li}+n$, a multichannel R-matrix analysis has been completed, providing much new structure information for the compound ${}^8\text{Li}$ system. These results are in very good agreement with recent theoretical model calculations, so that together the two provide considerable advancement in the state of our knowledge of ${}^8\text{Li}$. R-matrix analyses of ${}^{11}\text{B}+n$ and ${}^{13}\text{C}+n$ elastic scattering data have also been completed. For ${}^{13}\text{C}+n$ theoretical model calculations have also been carried out and comparisons of these theoretical results with the R-matrix analysis are made. The triplet quadrupole spectrometer (TQS) is now fully operational. Development of new detectors, techniques, data analysis codes and theoretical model codes for use with the TQS system is complete. Measurements of (n,z) cross sections for fusion reactor structural materials e.g. ${}^{58}\text{Ni}$ are currently underway. Construction of the long-flight-path tunnel for the swinger magnet facility has begun and development for this facility will continue in the coming year.

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A. INTRODUCTION

During the past year we have completed the work proposed and are on schedule in our commitments for data for the needs of the DOE/OFE fusion energy program. R-matrix analyses of data for several light nuclei have led to considerable new spectroscopic information for them. These in turn have sparked interesting new comparisons to model calculations. Initial measurements of (n,z) differential cross sections with the new triplet quadrupole spectrometer have been made.

Highlights of the results reported here include:

A breakthrough in the structure of ^8Li from the R-matrix analysis of $^7\text{Li}+n$, where no significant progress has been made in over twenty years (Section B-2).

A large-energy-range study of new states in ^{12}B from $\sigma(\theta)$ for $^{11}\text{B}(n,n)^{11}\text{B}$ (Section B-4).

New states in ^{14}C from R-matrix analysis of $\sigma(\theta)$ for $^{13}\text{C}+n$ together with core-coupling model (Section B-5).

Initial measurements of $\sigma(E_n, \theta)$ for $^{58}\text{Ni}(n,p)^{58}\text{Co}$ at 8 and 11 MeV with our new quadrupole spectrometer (Section C).

As part of our on-going research program to study the structure of light nuclei, we have completed an extensive set of measurements of $\sigma(\theta)$ for neutron inelastic scattering from ^6Li , ^{11}B and ^{13}C . These data together with the accompanying elastic data will allow us to better study the shell model and core-coupling models for the compound nuclei ^7Li , ^{12}B and ^{14}C . The inelastic data are also needed by DOE/OFE for fusion reactor design. Multiple scattering corrections are inherent to neutron work, and improvements in our ability to do these much more accurately have been made this year.

A new underground TOF tunnel approximately 30 meters long is now under construction at our laboratory. This facility will use a beam-swinging-magnet to bend the charged particle beam to vary the angles of scattering to give complete angular distributions with a single fixed flight path buried some 10 to 15 feet underground and exceptionally well shielded and collimated. This provides an unusually long and high quality flight path at a very small fraction of the usual cost. The low background and superior TOF resolution will make it possible to separate closely-spaced inelastic groups which would not otherwise be possible to study. Large area stacked detectors with high efficiency will be developed to maintain the best possible count rates.

B. Neutron Scattering Measurements

1. ${}^6\text{Li}+n$, ${}^7\text{Li}+n$ (H.D. Knox)

Measurements of neutron differential elastic and inelastic ($Q = -0.478$ MeV) scattering cross sections for ${}^7\text{Li}$ and differential elastic scattering cross sections for ${}^6\text{Li}$ for $2.3 \text{ MeV} \leq E_n \leq 4.08 \text{ MeV}$ have been completed. A 6.5 m flight path was used in these measurements in order to resolve the elastic and inelastic groups for ${}^7\text{Li}$. The scattering samples were in the shape of right circular cylinders and were contained in thin-wall aluminum cans. Both samples were 1.414 inches in diameter and 1.390 inches tall. The isotopic enrichment of the ${}^6\text{Li}$ sample was 98.7% and that of the ${}^7\text{Li}$ sample was 99.9%. Final cross sections are shown in figs. 1-3. These data combined with the earlier work of Lane (La 64) and previous work (Kn 79) at this laboratory provide a data base for both ${}^6\text{Li}+n$ and ${}^7\text{Li}+n$ elastic scattering up to $E_n \approx 8$ MeV. An R-matrix analysis of these ${}^7\text{Li}+n$ results along with other data is discussed in section C-2.

Measurements of neutron differential cross sections for inelastic scattering from the first excited state of ${}^6\text{Li}$ ($Q = -2.18$ MeV) are currently in progress. These measurements are being carried out with a 2.5 m flight path. Preliminary results are shown in fig. 4. These cross section measurements will be extended upwards in energy to $E_n \approx 8$ MeV in the upcoming year.

These measurements are on schedule with commitments made at the March 1979 coordination meeting at Durham, NC on cross section needs by DOE/OFE for fusion reactor designs.

Figure 1 Differential cross sections for neutrons elastically scattering from ^7Li .

Figure 2 Differential cross sections for neutrons inelastically scattered from the first excited state of ${}^7\text{Li}$.

Figure 3 Differential cross sections for neutrons elastically scattered from ${}^6\text{Li}$.

${}^6\text{Li}(\text{N}, \text{N}') {}^6\text{Li}^*(2.18)$
 Δ PRELIMINARY

Figure 4 Differential cross sections for neutrons inelastically scattered from the first excited state of ${}^6\text{Li}$.

2. $^{11}\text{B}(n,n')^{11}\text{B}^*$ (2.12, 4.45, 5.02) Measurements (P.E. Koehler)

Our survey of the $^{11}\text{B}(n,n')^{11}\text{B}^*$ (2.12) differential inelastic cross section has been essentially completed with our recent measurements of both the elastic and inelastic cross sections at 5.25, 5.75, 6.20, 6.40, 6.80 and 7.54 MeV. Except for the most recent measurements (5.25, 5.75 and 6.40 MeV), these elastic and inelastic cross sections and those reported for ^{11}B in last year's progress report (C00-2490-10) have been fully corrected for the effects of multiple scattering using a new code written at Ohio University (see section F-1). Figs. 5, 6 and 7 show angular distributions for neutron scattering to the 2.12 MeV level of ^{11}B at the six incident energies. In addition, a full distribution (9 angles) was obtained for neutrons scattered from the 4.45 MeV level at the incident neutron energies of 6.40 and 7.54 MeV. Partial distributions (2-5 angles) were obtained for the 4.45 MeV level at the incident neutron energies of 5.75, 6.20 and 6.80 MeV and for neutrons scattered from the 5.02 MeV level at the incident neutron energy of 7.54 MeV.

The differential inelastic cross sections at these energies are rather large (10 - 30 mb/sr). The shape and magnitude of the angular distributions change noticeably from one energy to another, giving evidence of resonance structure in the compound nucleus ^{12}B . It is hoped that our measurements now provide sufficient inelastic data so that when combined with our previous differential elastic cross section data (Wh 80) in an R-matrix analysis they will lead to new information on the level structure of ^{12}B from ~ 4 MeV to ~ 8 MeV incident neutron energy.

From an applied point of view, since these inelastic cross sections are of considerable size, our survey of this energy region should help provide a good knowledge of the inelastic cross sections for ^{11}B needed

FIGURE 5 Angular distributions of the differential cross sections for the elastic and 2.12 MeV first excited state of ^{11}B for the incident neutron energies of 6.20 and 6.80 MeV. The lines through the data points are Legendre polynomial fits. Our elastic data is compared to previous measurements at Ohio University by White et al.

FIGURE 6 Angular distributions of the differential cross sections of the 2.12 MeV first excited state and 4.45 MeV second excited state of ^{11}B for the incident energies of 5.25, 5.75 and 6.40 MeV. The lines through the data points are Legendre polynomial fits. At present, these data have not been corrected for multiple scattering.

FIGURE 7 Angular distributions of the differential cross sections for the elastic, 2.12 MeV first excited state and 4.45 MeV second excited state of ^{11}B at the incident neutron energy of 7.55 MeV. The lines through the data points are Legendre polynomial fits. Our elastic data is compared to previous measurements at Ohio University by White *et al.*

for proper shielding design for fusion reactors employing boron ($\sim 80\%$ ^{11}B) as a shielding constituent.

Also, in figs. 5 and 7 are comparisons of our elastic differential cross section measurements with previous measurements at Ohio University by White et al. (Wh 80), at the incident neutron energies for which our new differential inelastic cross section measurements have been corrected for the effects of multiple scattering. The agreement between the two sets of data is excellent in both shape and magnitude.

Previous differential measurements on ^{11}B are scarce so our data can be compared to data taken at other laboratories at only two incident energies. At an incident energy of 4.81 MeV, the differential inelastic (2.12 MeV level) angular distribution of Porter et al. (Po 70) is not in very good agreement with our measurements as shown in fig. 8. There is an approximate agreement in shape between the two measurements over the more limited angular range of the data of Porter et al. However, the integrated inelastic cross section of Porter et al. is only about two-thirds the size of ours at this energy. Likewise, the differential elastic cross section measurements of Porter et al. at this energy is not in good agreement with our measurements.

There is also disagreement between our present differential elastic and inelastic measurements and those of Hopkins et al. (Ho 69) at an incident energy of 7.54 MeV. As is shown in fig. 9 the disagreement is most pronounced at the forward angles. Also shown in figs. 8 and 9 are comparisons of our differential elastic cross section measurements and previous measurements made at this laboratory by White et al. (Wh 80). One should note the excellent agreement in both size and shape between these two sets of data.

FIGURE 8 Comparison of our differential cross section measurements for the elastic and 2.12 MeV first excited state of ^{11}B to those of Porter et al. at an incident neutron energy of 4.81 MeV. The lines through the data points are Legendre polynomial fits.

FIGURE 9 Comparison of our differential cross section measurements for the elastic, 2.12 MeV first excited state and 4.45 MeV second excited state of ^{11}B to those of Hopkins *et al.* and White *et al.* at an incident energy of 7.55 MeV. The lines through the data points are Legendre polynomial fits.

The sum of the integrated elastic plus first inelastic (2.12 MeV level) cross sections is in good agreement with the total cross section measurements of Auchampaugh et al. (Au 79). At an incident energy of 4.81 MeV, where only the 2.12 MeV first excited state is above threshold, the difference between the two sets of data is less than 4%. At higher energies where neutron scattering to the second and/or third inelastic levels ($Q = -4.45, -5.02$ MeV) is allowed, the difference between the sum of the integrated elastic plus first inelastic cross sections and the total cross section is substantial enough to indicate that the second and/or third inelastic levels may contribute a considerable amount ($\sim 100 - 200$ mb) to the total cross section. In fact, at an incident energy of 7.54 MeV, our differential inelastic cross section data yield an integrated cross section of 218 mb for the second inelastic (4.45 MeV level) state.

Fig. 10 shows the relative energy dependence of the Legendre polynomial coefficients for the expansion of our differential inelastic (2.12 MeV level) cross section measurements. Included in this graph are our results reported in last year's progress report (C00-2490-10) but not our most recent measurements at the incident energies of 5.25, 5.75 and 6.40 MeV, which are yet to be corrected for multiple scattering. The resonance structure indicated by these B-coefficients is most evident in R_0 and B_2 and to a lesser extent in the other 3 coefficients. At present, an R-matrix analysis of our differential inelastic measurements and previous differential elastic data from Ohio University is just underway. It is hoped that this analysis will enable us to determine more uniquely the energy level structure of ^{12}B over energy regions where our previous analysis of the differential elastic data was not entirely sufficient by itself.

FIGURE 10 Legendre expansion coefficients (arbitrary units) for the differential inelastic cross section from the 2.12 MeV level of ^{11}B .

3. $^{13}\text{C}(n,n)^{13}\text{C}$ and $^{13}\text{C}(n,n')^{13}\text{C}$ (3.09, 3.68 and 3.85) Measurements (D. Resler)

During the past year neutron differential elastic and inelastic cross section measurements for $^{13}\text{C}+n$ were made at 9 incident neutron energies ranging from 4.55 to 8.25 MeV. Previous measurements were made at this laboratory, reported in progress reports (C00-2490-9,10), at incident neutron energies below 6.50 MeV. Fig. 11 shows on a plot of total cross section (Au 79) the energies at which our inelastic measurements have been made. The data from 5.33 to 6.50 MeV were reported last year (C00-2490-10).

For incident neutron energies of 7.00, 7.55 and 8.25 MeV angular distributions for the elastic and first three inelastic groups have been obtained. At these energies the second and third inelastics were unresolved. The data is preliminary at this time and has not been corrected for multiple scattering. Fig. 12 shows the elastic and combined second-third inelastic distributions.

Recently, angular distributions were measured for the elastic and first inelastic groups at six incident neutron energies (4.55, 4.68, 4.74, 4.79, 4.84 and 4.89 MeV). As seen in the total cross section, there is a large peak in this energy region. The integrated elastic cross section also displays a peak, but the present preliminary results show no peak in the integrated first inelastic cross section. Shown in fig. 13 are the first inelastic distributions. Although the integrated first inelastic cross section simply decreases slightly over this energy range, the angular distributions display shape changes.

The R-matrix analysis of the initial survey measurements of elastic scattering is completed (see section B-5). The shape and magnitude changes of the elastic and inelastic distributions from 4.55 to 8.25 MeV give

Figure 11: Total cross section for neutrons on ^{13}C . Indicated are the energies at which we have measured differential inelastic cross sections of ^{13}C .

Figure 12 Angular distributions of the differential cross section of the elastic and combined inelastics for the 3.68 MeV second and 3.85 MeV third excited states of ^{13}C . The lines through the data are Legendre polynomial fits.

Figure 13 Angular distributions of the differential inelastic cross section for the 3.09 MeV first excited state of ^{13}C . The lines through the data are Legendre polynomial fits.

evidence of resonance structure in the compound nucleus ^{14}C . Thus it is hoped that an R-matrix analysis of this new data and future data will be able to determine the energy level structure of ^{14}C upwards from where the previous analysis stopped.

C. R-Matrix Studies and Model Calculations

1. Program Development (H.D. Knox, D.A. Resler)

Comprehensive multichannel multilevel R-matrix analyses for several light nuclei are currently underway at this laboratory. The R-matrix codes used in these analyses were originally developed here and in the past year have undergone several modifications. Two codes are currently in use. One code, ORMAP (Wh 80), is used for the analysis of neutron elastic scattering data only, while the second is used for simultaneous analysis of neutron elastic and inelastic scattering data. Both codes have been modified to include $\ell = 3$ orbital angular momentum channels. Programming changes have also been made in both codes to speed up the computations. In particular, rewriting of portions of the main "DO" loops in the programs have resulted in an order of magnitude decrease in the running times of the two codes. Finally, positive energy neutron induced charged particle reaction channels have been added to the second program. Subroutines for calculations of charged particle shifts and penetrabilities necessary for this modification were obtained from (Ra 79).

2. ${}^7\text{Li}+n$ (H.D. Knox, R.O. Lane)

Progress in understanding the structure of the ${}^8\text{Li}$ system has been exceedingly slow. Below about 10 MeV excitation energy, there are seven observed (Aj 79) unbound levels in this system as shown in fig. 14. Spin assignments have been made for only two of these levels, the 3^+ level at 2.255 MeV and the $J = 1$ level at 3.21 MeV. Both assignments were made more than twenty years ago and though additional structure studies (Fr 55, Pr 72, La 64) have been undertaken definite J^π assignments for other levels in ${}^8\text{Li}$ have not been made.

These earlier analyses of ${}^7\text{Li}+n$ experimental data typically consisted of analysis of differential cross section data for a single reaction channel or angle integrated data for a few reaction channels. A multi-channel multilevel R-matrix analysis of ${}^7\text{Li}+n$ scattering data has recently been completed at this laboratory. Included in this analysis were all available neutron differential cross section data for elastic scattering and inelastic scattering to the first two excited states of ${}^7\text{Li}$ up to $E_n \approx 8$ MeV as well as available ${}^7\text{Li}(n,n'\gamma){}^7\text{Li}^*(0.478)$ data.

The R-matrix code used in this analysis was developed at this laboratory and follows the formalism of Lane and Thomas (La 58) to calculate the scattering matrices for each J^π . The Legendre polynomial expansion coefficients, B_L , for each of the three reactions analyzed are then calculated using the formalism of Blatt and Biedenharn (Bl 52). The calculated B_L coefficients are finally compared with the experimental data with the goal of obtaining simultaneous fits to all reaction cross sections. Some of the experimental data that were analyzed in the present work are shown in figs. 15 and 16. Fig. 15 shows the Legendre polynomial expansion coefficients for neutron elastic scattering for ${}^7\text{Li}$, while

Figure 14 Level diagram for the ${}^8\text{Li}$ system prior to the present work.

Figure 15 Coefficients B_L in the Legendre polynomial expansion of the differential ${}^7\text{Li}(\text{n},\text{n}){}^7\text{Li}$ cross section. The curves are the R-matrix fits to the experimental data from the present work.

Figure 16 Coefficients B_L in the Legendre polynomial expansion of the differential inelastic ${}^7\text{Li}(n,n'){}^7\text{Li}^*(0.478)$ cross section. The curves are fits to the experimental data from the present R-matrix analysis.

similar coefficients for inelastic scattering from the first excited state ($Q = -0.478$ MeV) of ${}^7\text{Li}$ are shown in fig. 16.

In fitting these data numerous combinations of possible J^π values were tested for the levels in ${}^8\text{Li}$ indicated in fig. 14 and although reasonable fits were obtained for the data in some energy regions, satisfactory fits for the entire 0 to 8 MeV region could not be obtained for any of the cross sections analyzed. Good fits to the data over this large region of excitation energies were possible only with the assumption of the presence of six previously unknown levels in ${}^8\text{Li}$. Fig. 17 shows the final set of energy levels and J^π assignments that resulted from this study. All levels except the very narrow level at $E_x = 6.53$ MeV which was not included in the present analysis have now been given at least tentative J^π assignments. The curves in figs. 15 and 16 are the final R-matrix fits to the Legendre polynomial expansion coefficients. Fits to selected differential elastic and inelastic cross sections are shown in figs. 18 and 19, respectively. Calculated fits to all data are quite good over this very large range of neutron energies.

In fig. 17 along with the level diagram from the present work, the results of a cluster model calculation for ${}^8\text{Li}$ by Stöwe and Zahn (St 77) are shown. In that calculation the fragmentation ${}^7\text{Li}+n$, ${}^7\text{Li}^*+n$, ${}^5\text{He}+t$ and ${}^5\text{He}^*+t$ were taken into account providing results for the ${}^8\text{Li}$ system up to the ${}^5\text{He}+t$ threshold. The excellent agreement between the predicted level structure of ${}^8\text{Li}$ from the present work and the level scheme predicted by Stöwe and Zahn should be emphasized. All levels predicted by Stöwe and Zahn are also predicted in the present work. The ordering of the levels in the two calculations is almost the same. The location of only two levels, the 2^- and the 4^- , differ. For each level the cluster model

Figure 17 Final level structure and J^π assignments for ${}^8\text{Li}$ resulting from the present work. The results of the cluster model calculation of St 77 are also shown for comparison.

Figure 18 R-matrix fits from the present work to selected c.m. differential ${}^7\text{Li}(\text{n},\text{n}){}^7\text{Li}$ data.

Figure 19. R-matrix fits from the present work to selected c.m. differential ${}^7\text{Li}(n,n'){}^7\text{Li}(0.478)$ data.

calculation also predicted the dominant angular momentum channels in each particle channel. The present results are in very good agreement with these predictions also.

The results of this study represent a major advance in our understanding of the structure of the ^8Li system. With the multichannel multilevel R-matrix analysis, location of several new levels in ^8Li as well as J^π assignments for these levels was possible. The proposed level scheme for ^8Li is in good agreement with existing model calculations and with earlier analyses and also provides very good fits to available neutron differential scattering data over a very large region of excitation energies.

With the envisioned use of a lithium blanket for tritium breeding in proposed fusion reactors, a thorough knowledge of $^7\text{Li}+n$ reaction cross sections is essential. The present R-matrix analysis of ^8Li and the experimental $^7\text{Li}+n$ cross section measurements made at this laboratory should provide much new information on which new evaluations of these important cross sections can be made.

A paper describing the present R-matrix study has been submitted for publication in "Nuclear Physics."

3. ${}^6\text{Li}+n$ (H.D. Knox)

The study of neutron scattering and neutron induced reactions on ${}^6\text{Li}$ is of interest in both the fusion energy program and in neutron standards applications. To help provide evaluations of relevant cross sections for ${}^6\text{Li}$, a comprehensive multichannel multilevel R-matrix analysis of the ${}^7\text{Li}$ system has been undertaken. The neutron elastic, inelastic ($Q = -2.18$ MeV) and (n,α) channels are included in this analysis. Preliminary fits to the integrated elastic scattering cross section and integrated (n,α) cross section for $E_n < 1$ MeV are shown in fig. 20. The energy level scheme for ${}^7\text{Li}$ used in this calculation is similar to that used by Hale (Ha 75) in an analysis of the ${}^7\text{Li}$ system. In particular no bound positive parity states were assumed but a $\frac{3}{2}^+$ level is located at $E_x \approx 9.5$ MeV. The $\frac{1}{2}^+ \ell = 0$ contribution is included as a background R_0 . The experimental elastic scattering data shown here are from Lane et al. (La 64) and Asami et al. (As 70) and for the ${}^6\text{Li} (n,\alpha)t$ reaction, the data of Lamaze (La 76a) and Overley et al. (Ov 74) are shown.

Over the last few years measurements of neutron differential elastic scattering cross sections for ${}^6\text{Li}$ for $2 \text{ MeV} \leq 7.5 \text{ MeV}$ have been made at this laboratory. A series of neutron differential inelastic ($Q = -2.18$ MeV) cross section measurements for $E_n \geq 4.5$ MeV are currently underway (see section B-1). The present ${}^6\text{Li}+n$ R-matrix analysis will be extended upward in energy and will include these data as well as other available data for neutron induced reactions.

In our planned commitments to DOE/OFE for fusion related studies (March 1979 coordination meeting at Durham, NC), this analysis of ${}^6\text{Li}+n$ data was not scheduled to begin until FY 81. Completion of both the ${}^7\text{Li}+n$ analysis (section C-2) and revisions to the R-matrix analysis codes ahead of schedule has permitted an early start on this important work.

Figure 20 Preliminary fits to the ${}^6\text{Li}(n, n){}^6\text{Li}$ and ${}^7\text{Li}(n, \alpha)t$ angle integrated cross sections.

4. $^{11}\text{B}+\text{n}$ (R.O. Lane)

The final results for elastic scattering differential cross sections for $^{11}\text{B}+\text{n}$ have been published as "States in ^{12}B from Measurement and R-Matrix Analysis of $\sigma(\theta)$ for $^{11}\text{B}(\text{n},\text{n})^{11}\text{B}$," Nucl. Phys. A340 (1980) 13, by R.M. White, R.O. Lane, H.D. Knox and J.M. Cox. An abstract of this paper is given in a later section of this report. The completion of this work is in timely fulfillment of our previously proposed work including commitments made at the March 1979 coordination meeting at Durham, NC on cross section needs by DOE/OFE for fusion reactor designs.

5. $^{13}\text{C}+n$ (R.O. Lane, H.D. Knox, P. Hoffmann-Pinther, R.M. White[†] and G.F. Auchampaugh[#])

a) Measurements and R-Matrix Analysis

The manuscript for a complete journal article on this work is nearly ready for submission for publication, so only the main results will be given here. In our previous progress reports (C00-2490-9,10) the preliminary data and R-matrix results for neutrons elastically scattered from ^{13}C were given. Fig. 21 shows our differential elastic scattering cross sections, $\sigma_{el}(\theta)$, in terms of Legendre polynomial expansion coefficients, B_L , as a function of incident energy. The B_L are in the c.m. system while energies are in the laboratory system. The solid curve is the final R-matrix fit to the elastic data for $1.0 \leq E_n \leq 6.5$ MeV where the parameters for the fit are given in table 1. Shown at the top of the figure are the assignments for the states in ^{14}C for the fit. (The dotted line indicates the very narrow resonance at $E_n = 3.466$ omitted from this calculation.) Detailed discussions regarding this final analysis are given in the forthcoming manuscript. Except for the 1^+ state at $E_n = 3.35$ MeV, none of these states had been deduced in ^{14}C previous to the present experiment. From the reaction $^{15}\text{N}(d, ^3\text{He})^{14}\text{C}$, Kaschl et al. (Ka 71) observed the 1^+ state at $E_n = 3.35$ MeV ($E_x = 11.29$ MeV in ^{14}C). Also from the reaction $^{14}\text{C}(e, e')^{14}\text{C}$ Crannell et al. (Cr 77) also observed this 1^+ state. In both these experiments the widths obtained were 150 - 207 keV in agreement with our results. Other charged particle experiments, principally those of $^9\text{Be}(^6\text{Li}, p)^{14}\text{C}$ by Ajzenberg-Selove et al. (Aj 73) and $^{12}\text{C}(t, p)^{14}\text{C}$ by

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Figure 21

TABLE 1

R-matrix parameters for the levels in ^{14}C used in the calculated curves shown in figs. 21-25

No.	E_x (MeV)	E_n (lab) (MeV)	E_λ (MeV)	J^π	$\gamma_{\lambda c}, (\text{MeV})^{1/2}$				
					$s_{1/2}$	$p_{1/2}$	$p_{3/2}$	$d_{3/2}$	$d_{5/2}$
1	6.09		-3.20	1^-	0.70			0	
2	6.90		-2.10	0^-	0.70				
3	9.789	1.736	1.5951	3^-					0.240
4	9.806	1.754	1.629	1^-	0.13			0	
5	10.420	2.416	(2.2475)	$3^{(-)} \text{ a)}$					(0.123)
6	10.447	2.445	(2.270)	$(1^+, 2^\pm) \text{ b)}$		(0.059)	(0)		
7	10.502	2.504	(2.3247)	$\geq 1 \text{ c)}$; ($\Gamma < 6 \text{ keV}$)					
8	11.29	3.35	3.11	1^+		0.196	0.240		
9	11.395	3.466	(3.219)	$\geq 2 \text{ d)}$; ($\Gamma_\nu < 7 \text{ keV}$)					
10	11.44	3.51	3.25	1^-	0.20			0.90	
11	11.62	3.71	3.47	2^-				0.75	0.45
12	12.22	4.35	4.05	1^-	0.35			0.25	
13	12.61	4.77	4.44	$(3, 2)^- \text{ e)}$					(0.21)
14	13.85	6.1	5.7	$(1, 2)^- \text{ f)}$	(0.2)			(0.9)	

$$0^- R_{cc}^\infty: -0.15$$

$$b_c: 0$$

$$0^+ R_{cc}^\infty: 0.25$$

$$b_c: -0.25$$

$1^- R_{cc}^\infty :$	-0.15	0.55	
$b_c :$	0	-1.0	
$1^+ R_{cc}^\infty :$	0.25	0.55	
$b_c :$	-0.25	-0.25	
$2^- R_{cc}^\infty :$		0.55	0.05
$b_c :$		-1.0	-1.0
$2^+ R_{cc}^\infty :$		0.55 g)	
$b_c :$		- .25 g)	
$3^- R_{cc}^\infty :$			0.05
$b_c :$			-1.0

A channel radius of $a_c = 4.5F$ was taken for all channels. Only diagonal elements of the $R_{c'c}^{\infty J^\pi}$ background matrix were employed in the final best fit and are listed under each J^π value. All quantities other than E_n (lab) are in the center-of-mass system. Parentheses on E_λ , $\gamma_{\lambda c}$ indicates values may change for assumptions other than those used in calculated curve.

- For $J^\pi = 3^+$, $\gamma_{\ell=3} = 0.37$
- Curves and parameters for $J^\pi = 1^+$; $\gamma_{p_{3/2}} = 0$ for convenience only.
- Curves and E_λ for $J^\pi = 2^+$; $\gamma_{p_{3/2}} = 0.03$, $\gamma_{f_{5/2}} = 0$.
- Curves and E_λ for $J^\pi = 2^+$; $\gamma_{f_{7/2}} = 0.11$, $\gamma_{p_{3/2}} = 0$.
- Curves and parameters for $J^\pi = 3^-$. Best 2^- fit gave.
- Curves and parameters for $J^\pi = 1^-$. Best 2^- fit gave.
- $R_{cc}^\infty = 0$ and $b_c = -2.5$ for all $\ell = 3$ cases.

Mordechai et al. (Mo 78) either did not observe these broad states or were not able to make definite assignments to them.

In order to make a more complete study of ^{14}C , the total neutron cross section data of Auchampaugh et al. (Au 79) for ^{13}C were also included in the R-matrix analysis to determine the final parameters in table 1. Fig. 22 shows the total cross section data points of Auchampaugh et al., divided by 4π for comparison to the coefficient B_0 (where $\sigma_{el} = 4\pi B_0$) obtained in the R-matrix calculation for the elastic scattering cross section. The R-matrix program used here (ORMAP) calculates only elastic scattering, σ_{el} , and is valid for analyzing σ_T up to $E_n \approx 3.3$ MeV, the first inelastic threshold, and reasonably valid up to $E_n \approx 4$ MeV, the second inelastic threshold. The cross section for the first inelastic group has been shown (Ko 79) to be very small at most energies and this fact is evident below $E_n \approx 4.2$ MeV from the smallness of the difference between the data points for $\sigma_T/4\pi$ (Au 79) in fig. 22 and the calculated curve which fits B_0 for elastic scattering rather well in fig. 21. Above $E_n \approx 4.5$ the difference becomes substantial so that the neglect of the inelastic channels for the calculation of the elastic reduces the validity of the calculation so that unique assignments could no longer be made.

Below $E_n \approx 3.5$ MeV the approximation $\sigma_T = \sigma_{el}$ is quite valid for nearly all of the interval and the program was used to extract R-matrix parameters of the states in ^{14}C from the data for σ_T . Reduced widths in the $s_{1/2}$ channel for bound states of 1^- at $E_x = 6.09$ MeV and 0^- at 6.90 MeV were obtained from stripping data and produced the pronounced rise in B_0 (or σ_T) as the energy tends toward zero in fig. 22. The R-matrix fit below ~ 1 MeV was obtained from the shape of the data of Cohn et al. (Co 61) normalized to the data of Auchampaugh et al. Fig. 23

Figure 23

Figure 22

shows the final R-matrix fit to the nearly coincident resonances of 3^- at $E_n = 1.736$ MeV and 1^- at 1.754 MeV. In all previous work these were not resolved but were analyzed as one state, which led to conflicting assignments. Fig. 24 shows the final R-matrix fit to the group of three resonances in the vicinity of $E_n = 2.4 - 2.5$ MeV. The assignments and best R-matrix fit are shown on fig. 24 for the parameters given in table 1. Mordechai et al., from $^{12}\text{C}(t,p)^{14}\text{C}$ observed the two lower-energy states together as one unresolved peak, but claim that the lower one was stronger and had $J^\pi = 2^+$ from their distorted wave analysis. The dashed curve in fig. 24 clearly shows that $J^\pi = 2^+$ cannot fit the neutron total cross section data for this resonance. The measurements of Auchampaugh et al., are the first to resolve these two states sufficiently to make a clear J - assignment. The fit for $J^\pi = 3^-$ was definitely better than that for 3^+ , but an unambiguous assignment for parity could not be made with certainty, so the preferred assignment of $J^\pi = 3^{(-)}$ is given.

Fig. 25 shows the best fit of $J \geq 2$ to the very narrow resonance at $E_n = 3.466$ MeV. The parity could not be determined. No values of $J \leq 1$ could fit these data. From the $^{12}\text{C}(t,p)^{14}\text{C}$ reaction Mordechai et al., observe a sharp peak at $E_x = 11.398$ MeV in ^{14}C which corresponds almost exactly (see table 1) to this sharp resonance in σ_T . They give an unambiguous assignment of 1^- to this state in obvious disagreement with the present work. The dashed curve in fig. 25 shows the result for a 1^- assignment which clearly disagrees with the data. The 1^- state at $E_x = 11.44$ MeV observed in the present experiment could not possibly be the 1^- state assigned by Mordechai et al., because the very broad state observed in this neutron work has a reduced width of $\gamma_{d3/2}^2 = 0.8$ MeV.

The states assigned in ^{14}C from this work are labeled in fig. 22 to

Figure 25

Figure 24

summarize the present results. Solid curves in all figures are final R-matrix calculations for the Legendre polynomial coefficients for elastic scattering and are derived from the final parameters given in table 1. Fig. 26 shows the energy-levels of ^{14}C derived from this and previous work where the total neutron cross section together with inelastic thresholds are shown on the right side as guides to relate the resonances to the corresponding levels in ^{14}C .

Previous to this work very few of the levels of ^{14}C above the neutron separation energy were known with definite J^π assignments. This work provides considerably more insight to the structure of ^{14}C as described in the following section on theoretical model calculations for ^{14}C and comparisons to results of the present experiment.

Figure 26

6. ^{14}C Core-Coupling Model Calculations (P. Hoffmann-Pinther)

Several model calculations (Wa 60, Co 68, Go 68) have been made to interpret the low lying positive parity level structure of the $A = 14$ system. These calculations were restricted to energies below those directly studied in the present experiment. True (Tr 63) performed a shell model calculation for states in ^{14}N corresponding to energies of the present experiment in which he assumed two nucleons in the $1p_{1/2}$, $2s$ and $1d$ orbitals coupled to a closed ^{12}C core. From such a restricted basis positive parity, $T = 1$, states at energies of this experiment can only arise from two nucleons in the sd shell, and thus are not likely to be populated in elastic neutron scattering from ^{13}C .

Fortune et al. (Fo 78) performed calculations for positive parity states in ^{14}C by also assuming two neutrons in the sd shell coupled to $^{12}\text{C}_{\text{g.s.}}$ using the effective matrix elements of Lawson et al. (La 76b) and Kuo (Ku 66). As mentioned above these states are not likely to be observed in the present experiment.

However, there is a singular positive parity state which is clearly identified in the present experiment at $E_x = 11.29$ MeV with $J^\pi = 1^+$. This state is formed by both $p_{1/2}$ and $p_{3/2}$ neutrons incident on $^{13}\text{C}_{\text{g.s.}}$. This is the only 1^+ state observed so far in ^{14}C and is presumably composed predominantly of the proton configurations $(1p_{1/2}^{-1}, 1p_{3/2}^{-1})_{1^+}$ and a closed $1p$ shell for the neutrons (Ka 71, Li 72). Assuming that $^{13}\text{C}_{\text{g.s.}}$ contains this configuration for the protons plus $1p_{1/2}^{-1}$ or $1p_{3/2}^{-1}$ for the neutrons, the 1^+ state can be formed by closing the $1p$ neutron shell with the incident neutron.

An extensive shell model calculation for the $1p$ shell nuclei, using effective TBME, has been carried out by Cohen and Kurath (Co 65), who

also have calculated spectroscopic factors (Co 67) for stripping leading to positive parity $T = 1$ states in $A = 14$. For a 1^+ , $T = 1$ state at $E_x = 11.783$ MeV in ^{14}N (9.41 MeV in ^{14}C), they give spectroscopic factors of $\sim 10^{-3}$ for transfer of a $1p_{3/2}$ nucleon and $\sim 10^{-4}$ for that of a $1p_{1/2}$ nucleon which would yield relative reduced widths of the same magnitude (as discussed later). From table 2, the relative reduced width, $\theta_{\lambda c}^2$, is 0.017 for the $p_{3/2}$ and 0.12 for the $p_{1/2}$ neutron transfer, that is several orders of magnitude greater than the predicted values. However, little confidence can be placed in such a small calculated value or in the location of the state because it may be beyond the range of calculation.

Richter and de Kock (Ri 79) used the wavefunctions obtained by Saayman et al. (Sa 73) in a MSDI global calculation for nuclei with $10 \leq A \leq 14$ to calculate one-particle spectroscopic factors for these nuclei. The calculated spectroscopic factors for the only $T = 1$ unbound state in $A = 14$, i.e. the 1^+ state at 10.59 MeV in ^{14}N (8.22 MeV in ^{14}C), are of the order of 10^{-3} . Thus the calculations of both Cohen and Saayman severely underestimate the widths of this state as observed in this and other experiments (Ka 71, Cr 77). A separate fit by Saayman to $A = 14$ only, and which does include the 1^+ level at 13.75 and 3.95 MeV and two other 2^+ levels, yields as expected, a better overall fit for ^{14}N yielding a 1^+ level at an excitation equivalent to 10.84 MeV in ^{14}C . However, the main amplitude in the wavefunction changes little so that the spectroscopic factor is probably little affected. This is also the case for a separate fit for $A = 13$.

A weak coupling calculation by Lie (Li 72) for $A = 14$ (but fixing on ^{14}N) using an ^{16}O core yields a 1^+ $T = 1$ state at an excitation energy of 9.68 MeV in ^{14}C . This state is a 99% pure $(\pi p_{1/2}^{-1}, \pi p_{3/2}^{-1})$ configuration, in

TABLE 2

Energy spectrum and relative reduced widths from the present experiment and (Aj 76)
and the calculated spectra and relative reduced widths

EXPERIMENTAL					CALCULATED									
E_x (MeV)	J^π	θ^2			E_x^a	J^π	θ^2			E_x^b	J^π	θ^2		
		$s_{1/2}$	$d_{3/2}$	$d_{5/2}$			$s_{1/2}$	$d_{3/2}$	$d_{5/2}$			$s_{1/2}$	$d_{3/2}$	$d_{5/2}$
6.09	1^-	0.15	0		6.34	1^-	0.15			6.19	1^-	0.15	0.06	
6.73	3^-				6.76	3^-			0.35	6.52	3^-			0.36
6.90	0^-	0.15			7.08	0^-	0.15		0.35	7.44	2^-		0.12	0.29
7.34	2^-				7.67	2^-			0.32	7.60	0^-	0.17		
					9.62	2^-		0.0	0.02					
9.79	3^-			0.02										
9.81	1^-				9.84	3^-			0.02					
					10.18	1^-	0.01	0.02						
										10.36	3^-			0.04
10.42	$3^{(-)}$													
10.45	$(1^+, 2^+)$													
10.53	> 1 $(3^+)^c$				10.50	1^-		0.20						
										10.55	2^-		0.24	0.21
										10.58	1^-	0.05		
					10.87	2^-		0.02						
11.29	1^+				11.32	4^-								
11.40	≥ 2													
11.44	1^-	0.01	0.25		11.48	2^-		0.12						

EXPERIMENTAL				
E_x (MeV)	J^π	θ^2		
		$s_{1/2}$	$d_{3/2}$	$d_{5/2}$
11.62	2^-		0.17	0.06
11.74	(5^-)			
12.22	1^-	0.04	0.02	
12.61	$(3,2)^-$			.01
	$(1^-)^c$			
12.87	$(2^+, 3^-)^c$			
	$(4,5)^d$			
12.96	$(1^-)^c$			
	$(3,4)^d$			

13.85 $(1,2)^-$

Many levels, no assignments

CALCULATED									
E_x^a	J^π	θ^2			E_x^b	J^π	θ^2		
		$s_{1/2}$	$d_{3/2}$	$d_{5/2}$			$s_{1/2}$	$d_{3/2}$	$d_{5/2}$
					11.51	2^-		0.09	
11.77	3^-								
					12.00	1^-		0.21	
					12.13	4^-			
12.24	1^-	0.01	0.04						
13.11	3^-								
13.41	2^-		0.02	0.06					
13.43	0^-	0.04							
13.61	1^-		0.08						
13.65	3^-			0.03					
14.30	2^-		0.01		14.30	$5^-, 1^-$			
14.58	5^-				14.43	3^-			0.03

Experimental $\theta^2 = \frac{2Ma^2}{3h^2} \gamma^2$, $a = 4.5f$. Relative reduced widths less than 10^{-2} are not tabulated.

- a) Present calculation
- b) MDR
- c) Mo 78
- d) Aj 76

agreement with the configurations of Cohen and Kurath (Co 67) and Mangelson (Ma 68). The two hole configuration is in agreement with the results of the $^{15}\text{N}(d, ^3\text{He})^{14}\text{C}$ experiment of Kaschl et al. (Ka 71).

Shell model calculations for the non-normal parity states in $A = 14$ have been carried out by Sebe (Se 63) and Richter (Ri 79) for excitation energies corresponding up to about 8 MeV in ^{14}C . True (Tr 63) predicts two unbound states while the calculation of Hsieh and Horie (Hs 70) yields three such states. Lie (Li 72) has extended his calculation to near the 11 MeV region and predicts several unbound states. The spectrum of negative parity states of ^{14}C for excitation energies observed in the present experiment and the $^{12}\text{C}(t, p)^{14}\text{C}$ experiment (Mo 78) has been calculated in the core-coupling model by the authors, and by Millener and Darema-Rogers (Mi 80) who have used effective interactions.

The present core-coupling model includes the 0^+ ground state and 2^+ first excited state in the $(A-2)$ core, ^{12}C , in order to include core excitations in the region (Mo 78).

The Hamiltonian for the core-coupling calculation is

$$H = H_c + \sum_{n=1}^2 H_n - \xi \sum_{n=1}^2 \bar{J}_c \cdot \bar{j}_n - \eta \sum_{n=1}^2 Q_c \cdot Q_n \\ + V_0 [(1 - \alpha) + \alpha(\vec{\sigma}_1 \cdot \vec{\sigma}_2)] \delta(\vec{r}_1 - \vec{r}_2)$$

where H_c and H_n are the Hamiltonians for the core and neutrons; J_c and j_n are the angular momentum of the core and neutrons respectively, with Q_c and Q_n the mass quadrupole operators for the core and neutrons. The strength parameters are ξ , η , V_0 and α . The wavefunctions are expressed as $|E_{\alpha} J_c(j_1 j_2) J_c^{IM}\rangle = \sum_{J_1 J_2} \langle j_1 j_2 J_c : IE_{\alpha} | [(J_1 J_2) J]_A J_c : IM \rangle$. The Hamiltonian

$H_c + H_n$ is diagonal in this scheme so that the energy of the core replaces

H_c and is taken from ^{12}C data, while single particle energies replace H_n .

The reduced matrix element for the core $\langle 0^+ || Q_c || 2^+ \rangle$ is deduced from the $2^+ \rightarrow 0^+$ transition in ^{12}C while the $\langle 2^+ || Q_c || 2^+ \rangle$ matrix element is determined by the relation (Bi 75)

$$\frac{\langle 2^+ || Q_c || 2^+ \rangle}{\langle 0^+ || Q_c || 2^+ \rangle} = + \sqrt{\frac{10}{7}}$$

The single particle energies differences are chosen initially to be approximately those found in ^{13}C while ξ , η , V_0 and α are determined in the fitting. These values are given in the following table.

^{14}C PARAMETERS

Single Particle		Core		Coupling	δ
j	E_j (MeV)	J_c	E_c (MeV)		
$s_{1/2}$	5.700	0^+	0	$\xi(\text{MeV}) = -0.330$	$V_0(\text{MeV } f^3) = 100.0$
$d_{5/2}$	6.000	2^+	4.43	$\eta(\text{MeV } \text{fm}^{-2}) = 0.210$	$\alpha = 0.400$
$d_{3/2}$	11.000				

Spectroscopic factors are easily obtained in the model calculations. These spectroscopic factors have been used to calculate relative reduced widths using the relationship (Ma 60)

$$\theta^2 = S\theta_0^2$$

where S is the spectroscopic factor and θ_0^2 is a single particle reduced width.

In the core-coupling calculation spectroscopic factors are obtained from the wavefunctions by a simple recoupling in which the wavefunction represents an (sd) neutron coupled to the ground state of ^{13}C taken to

be $[0^+(^{12}\text{C}) \times p_{1/2}]_{1/2}$. This assumption is reasonable in view of the relative pure ($\sim 70\%$) $p_{1/2}$ nature of the ground state of ^{13}C (Sa 73, Da 79). The spectroscopic factors are given by

$$S_{lj} = |\langle 1/2 \ j J J_c : I E_\alpha \rangle|^2$$

In the calculation of Millener and Darema-Rogers the spectroscopic factor is simply related to the square of the single particle coefficient of fractional parentage for the appropriate (sd) neutron coupled to $^{13}\text{C}_{\text{g.s.}}$. Lie also calculates spectroscopic factors as simple overlaps. Those values have to be multiplied by a factor of 2 for the ^{14}C core.

The calculated spectra and spectroscopic information for the negative parity states from Millener and Darcma-Rogers and from the present calculations together with the results of the present experiment are summarized in table 2. Fig. 27 presents the above calculated spectra, the spectrum of Lie adjusted to ^{14}C , and the experimental spectrum. Possible correspondence between experimental levels and calculated states are based on the energies and relative reduced widths of levels given in table 2. The calculated relative reduced widths, $\theta_{s_{1/2}}^2$, were normalized to the 0^- experimental level so that $(\theta_0^2)_{s_{1/2}} = 0.176$. However, no 3^- bound state is available in this experiment to normalize $(\theta_0^2)_{d_{5/2}}$ so an attempt was made to normalize to the value of θ^2 obtained from the $^{13}\text{C}(d,p)^{14}\text{C}$ data of Glover and Jones (Gl 66). However, poor results were obtained when the assumption $(\theta_0^2)_{d_{3/2}} = (\theta_0^2)_{d_{5/2}}$ with $(\theta_0^2)_{5/2}$ determined from the data of Glover and Jones was used to calculate $\theta_{d_{3/2}}^2$ and $\theta_{d_{5/2}}^2$. The spectroscopic factors $S_{s_{1/2}}$, $S_{d_{3/2}}$ and $S_{d_{5/2}}$ are large in both the core-coupling and

Figure 27 Experimental and calculated levels, spins and parities condensed from table . Experimental levels seen in different experiments and which differ by 6 keV or less are assumed to be the same level. The first assignments for the levels (a) are from $^{12}\text{C}(t, p)$ and the second from (AJ 76).

effective interaction calculation of Millener and Darema-Rogers (hereafter referred to as MDR) and that of Lie (when adjusted to ^{14}C). These calculated values of $S_{s_{1/2}}$ and $S_{d_{5/2}}$ are in fairly good agreement with the values derived from the $^{13}\text{C}(\vec{d},p)^{14}\text{C}$ data of Datta et al. (Da 78) for the 1^- and 2^- bound states. Datta et al. does not mention the role of the $\ell=2, j=3/2$ transfer in the DWBA calculations. In view of the agreement with this data and the large uncertainties in the widths we chose $(\theta_0^2)_{d_{3/2}} = (\theta_0^2)_{d_{5/2}} = 0.40$ which also was used in the calculations of Lie (Li 72). It is seen from fig. 27 that all of the calculations reproduce most of the spin and parities of the levels for which spin and parity are assigned. For the bound states, all calculations, as expected, reproduce the spin and parities. Near 10 MeV all calculations show a 1^- , 2^- , 3^- set of states. Of these the 3^- and 1^- states of MDR and the present core-coupling calculation are identified with the 3^- and 1^- experimental levels at 9.79 and 9.81 MeV respectively. The calculated reduced widths for these levels are small in all the calculations, in agreement with experiment.

In the core-coupling calculation the above 2^- state is essentially a core excited state which yields small widths. The corresponding 2^- state calculated by Lie is also the most complex state reported there and yields small widths. However, in the MDR calculation the 2^- state in question has $\theta_{d_{3/2}}^2 = 0.24$ and $\theta_{d_{5/2}}^2 = 0.21$ and is associated with the experimental level at 11.62 MeV.

The experimental spectrum has three closely spaced levels at 10.42, 10.45 and 10.50 MeV. The first of these is assigned $J^\pi = 3^{(-)}$ while the next two have possible assignments in this experiment of $(1^+, 2^\pm)$ and ≥ 1 respectively. The level at 10.50 MeV also has been suggested to be

$J^\pi = (3^+)$ by Fortune (Fo 78). None of the calculations yields a 3^- state in this region; the nearest, occurring in the core coupling calculation is at 11.77 MeV with $\theta_{d_{5/2}}^2 < 10^{-3}$.

The calculations all yield several states which corresponded to several levels in the next group of experimental levels which occurs above 11 MeV and for which there are several J^π assignments. There are two experimental levels, with $J^\pi = 1^-$; one at 11.44 MeV, the other at 12.21 MeV. The core-coupling model yields two $J^\pi = 1^-$ states in this region. The lowest of these states, at 10.50 MeV, is somewhat low in energy but yields a value for $\theta_{d_{3/2}}^2$ in good agreement with the experimental value for the 11.44 MeV level. The MDR calculation yields only one 1^- state in the region, at 12.00 MeV, with $\theta_{d_{3/2}}^2$ also in good agreement with this same experimental value. In both these calculations $\theta_{d_{5/2}}^2 < 10^{-3}$ or smaller. The calculation of Lie, which also yields two 1^- states for comparison, yields no relative reduced width for the lower state because of the absence of appropriate components in the wavefunction. No data are presented for the upper state. The relative widths of the second 1^- state in the core-coupling model are in good agreement with the experimental values for the 12.21 MeV level.

The states corresponding to the 2^- level at 11.62 MeV are the states at 11.48 MeV in the core-coupling calculation and 10.55 MeV in the MDR calculation. The calculation of Lie yields a 2^- state at 10.94 MeV with $\theta_{d_{3/2}}^2 = 0.08$ while the experimental value is $\theta_{d_{5/2}}^2 = 0.17$. All three models yield a negative parity level with $J = 4$ and which has not been seen. In addition, the MDR and the core-coupling calculations each predict another weak 2^- level in this region.

The calculated 5^- state just above 14 MeV may be associated with the level at 11.76 MeV with a tentative 5^- assignment.

Correspondence between experimental levels above 12.50 MeV will have to await resolution of the uncertainties in the experimental assignments in the region and a firm parity assignment for the level at 10.42 MeV.

As indicated above, the three calculations reproduce much of the spectrum of negative parity states. In spite of apparent differences such as the prediction of a weak 2^- state near 10 MeV, the calculations share much in common. In fact a calculation by Darema-Rogers (Da 79) with different parameters in the effective interaction calculation yields a weak 2^- state near 10 MeV. However, a weak 1^- state remains up near 14 MeV in contrast to the weak 1^- state in the vicinity of 11 MeV in the two other calculations.

In the weak coupling limit the MDR calculation can be interpreted in terms of a sd nucleon coupled to the ground and lowest excited states of ^{13}C . Effectively this also happens in the weak-coupling calculation of Lie when 3 holes are coupled to $J^\pi = 1/2^-, 3/2^-$ ($T = 1/2$) states at 0.00 and 3.68 MeV, to which an sd nucleon is coupled. In the core-coupling model the excitations are treated collectively but all the excitation in all the calculations are similar if in the core coupling calculation one views the $1p_{1/2}$ nucleon coupled to the ground and first excited states of ^{12}C . Thus the similarities in the results are not totally unexpected.

The present experiment yields much new information on the structure of the ^{14}C nucleus; while calculations show that the spectrum of negative parity states can be interpreted with a considerable degree of success in terms of simple models and uncomplicated configurations.

D. Triplet Quadrupole Spectrometer

1. Introduction

Although the Triplet Quadrupole Spectrometer (TQS) was completed during the last contract year, we still consider it to be a "new" instrument and, therefore, we have expended considerable effort in developing detector and analysis systems, characterizing the system response and searching for any possible experimental anisotropies.

Measurements of $^{58}\text{Ni}(n,p)$ plus $^{58}\text{Ni}(n,n'p)$ in the 8 - 11 MeV region are in progress and should be completed by the end of this contract year.

2. $^{58}\text{Ni}(n,z)$ Measurements (G. Randers-Pehrson, J. Rapaport and R. Finlay)

The first series of measurements on the TQS for DOE is the study of $^{58}\text{Ni}(n,p)$ in the region where the $(n,n'p)$ channel opens. This problem is interesting because work at Lawrence Livermore Laboratory indicates that in nuclei where the neutron separation energy is greater than the proton separation energy, it is possible to inelastically scatter to a group of states in the target nucleus for which the neutron channel is closed but proton decay is still possible (Gr 77). The decay of these states results in an excess of low energy protons which are only in competition with γ -radiation.

Preliminary measurements were made at 0° , 60° and 120° using 8 and 11 MeV neutrons from the $^2\text{H}(d,n)$ source and a traditional $\Delta E, E$ telescope at the focal point of the TQS. Sample spectra are shown in fig. 28. It is clear that the low energy yield is higher at 11 MeV than at 8 MeV. The lower limit on the measured proton energy is due to the stopping of particles within the ΔE detector. This problem was addressed through the construction of a thin film plus channel plate detector as a first element of the telescope as described in the next section of this report. Fig. 29 displays the resulting spectra at 120° from 10 and 11 MeV neutron bombardment of ^{58}Ni .

We found considerable forward peaking of the low-energy protons measured at 11 MeV, contrary to what we expect for a two-stage evaporation process. Part of the low energy yield is undoubtedly due to (n,p) reactions originating from neutrons in the (d,np) continuum inherent to the source reaction. The next experimental run, before the end of this contract year, will deal with this latter complication by using a dual gas cell with the second cell filled with ^3He to simulate the breakup spectrum without the discrete peak, allowing subtraction of the contaminating continuum (Gr 79)

Figure 28 Proton yield measured with standard $\Delta E + E$ telescope. Note that the lowest energy detectable with this system is 1.8 MeV. The 8 MeV spectrum is for 0° , while the 10.9 MeV spectrum is at 120° .

Figure 29 Yield of protons at 120° from neutron bombardment of ^{58}Ni .

We have also made an exploratory run at 21.7 MeV for $^{58}\text{Ni}(n,z)$. That experiment was unfortunately shortened by accelerator instabilities that required a belt change. The proton background at that energy is very high due to $\text{Pb}(n,p)$ interactions in the lining of the target chamber. It appears that proton measurements above 20 MeV will be prohibitively difficult and, therefore, future runs in that energy range will be optimized for measurements of α -particle cross sections.

3. Channel Plate Detector (G. Randers-Pehrson)

One of the ways to reduce background in the TQS is to require a coincidence between two charged particle detectors. The requirement that the first detector be thin compared to the particle range is a very serious constraint when looking at low energy particles: the thinnest available transmission mounted detectors will stop 1.5 MeV protons and 4.5 MeV alpha particles.

We have developed an electron-emitting foil plus microchannel plate detector for use in low energy particle measurements (see fig. 30). The thin foil is supported over an aperture in a cylindrical surface by a high transmission grid. A nearby accelerating grid directs the kinematically emitted electrons toward a chevron microchannel plate with a gain of $\approx 10^7$ which is followed by a fast discriminator. The coincidence of this discriminator output with the signal from a large area solid state detector is required for a valid event.

The average number of electrons emitted from a film when a light ion passes through is small, so there is some probability that no electrons are detected. This fact results in a detection efficiency less than unity as displayed in fig. 31. The curve drawn here is based on an assumption that the number of electrons detected is described by a Poisson distribution with the average number proportional to the ion energy loss rate. Various surface treatments for the foil were attempted to increase the average number of electrons emitted. More experiments on these treatments are planned. At present the best surface is from magnesium oxide smoke from a burning ribbon.

Figure 30 Microchannel plate detector for coincidence measurement of low energy ions entering a stopping solid state detector at the focal points of the TQS. The coincidence requirement eliminates background events produced by neutrons and γ -rays interacting within the volume of the main detector.

Figure 31 Efficiency of carbon foil plus channel plate detector designed for measurement of low energy ions.

4. Computer Programs (G. Randers-Pehrson)

Experimental data for the experiments in this lab are handled by three computers. Our minicomputer does on-line analysis event-by-event. The IBM 1800 is used for mass storage of all data spectra with flexible recall and display capabilities, some off-line but immediate data reduction and also input and printer/plotter output of files for the University IBM 370. Major data reduction and theoretical analysis is performed on the 370.

Memory size of the minicomputer was recently increased to 16K words (soon to be doubled again to 32K). This larger memory allows storage of spectra with higher resolution and allows greater flexibility of writing programs which help monitor the progress of an experiment. The executive language has been evolving rapidly with careful attention to features which we experimenters propose.

The essential feature of the on-line analysis is to use a two-parameter input, namely Energy vs. Time-of-Flight, to calculate the mass of the detected particle and thereby store separate spectra for each mass present. A sample mass spectrum from a $^{58}\text{Ni}+n$ experiment is shown in fig. 32a. The corresponding proton and α -particle spectra are shown in fig. 32b.

Special programming for the IBM 1800 system has been unnecessary because the package of programs already present is quite admirably flexible.

Once the data are transferred to the IBM 370, there are three stages of analysis to be performed. First, the response of the TQS itself and the detector telescope are unfolded from the measured spectra using the program TANKA. This program was written last year but has been upgraded for faster execution with less memory and greater flexibility. TANKA

Figure 32 Yield of charged particles emitted from bombarding ^{58}Ni with 11 MeV neutrons. The width of the energy spectra are determined by the transmission of the TQS. The energy and time of flight are folded together to produce the mass spectrum.

predicts the thick target yield from a polyethylene target using the $^1\text{H}(n,p)$ cross section and energy loss rate. By comparing a measured Ch_2 spectrum with this prediction, TANKA obtains the transmission characteristics of the TQS. The transmission function is used to extract yields from measured spectra. Normalization is relative to $^1\text{H}(n,p)$ by the use of a fixed neutron monitor. TANKA also combines the results of a series of spectra obtained with as many settings of the magnetic field as necessary to cover the range of charged particle energies of interest.

The second stage of data reduction is to extract the effects of target thickness. The need for this correction can be minimized by using thinner targets, but since TQS measurements are already slow, it is preferable to use unfolding techniques when possible. For this purpose we obtained the unfolding program LSM from the University of California, Davis (Jo 80) and adapted it for operation on the 370. The program is operational and accepts data in the format of TANKA output. LSM was designed for biological materials and, therefore, its energy loss tables are for carbon, nitrogen and oxygen only. These tables will be expanded before the end of this year in order to analyze $^{58}\text{Ni}(n,\gamma)$ data.

The third stage of analysis is to compare the cross sections with predictions of various models. We have two Hauser-Feshbach codes which will be used: HELENE and HF. The latter is a multi-stage code brought to us from Lawrence Livermore Laboratory by S. Grimes when he was here. We also expect to make comparisons with the "Uhl" code--predictions of which are to be sent to us by M. Divadeenam of BNL who is the evaluator for nickel.

Program development needed for the TQS is largely complete except for evolutionary changes. We acknowledge that programming for the mini is the work of Don Carter and Dennis Hunt. Programming for data reduction was

a cooperative effort among the people supported by DOE and others in the lab who will use the TQS, particularly P. Grabmayr (supported by NCI) and V. Kulkarni (NSF). In the running and testing of HELENE and HF, we have enjoyed the help of Professor C. Brient.

5. Miscellaneous Developments (G. Randers-Pehrson)

Other developments which absorbed a lot of our effort include changes in the vacuum system for the TQS. Because we use an LN_2 cooled Germanium detector, we need an excellent vacuum. Although an ion pump already present in the lab had provided adequate vacuum, the problem of persuading it to start pumping caused us to purchase a helium refrigerated cryopump. After installation, the cryopump operation has been excellent with very easy transfer from rough vacuum. A new, larger detector vacuum box was also installed at the same time.

During a measurement to examine variation of the TQS transmission function across the area of the radiator, we found changes of the focal properties as the magnet was moved around in angle. These changes were attributed to bending of the support structure because the concrete floor is not precisely level. This problem was solved by laying down a sheet metal track in the low areas while cutting away paint and concrete from the highest spots. The spectrometer can now be easily moved by one person.

Another change was to install a large indicator to allow precisely repeatable location of targets. Settings better than 0.02 cm are easily obtained.

E. Swinger Magnet Facility (C. Brient, R. Finlay, J. Rapaport and G. Randers-Pehrson)

The rebuilding of the MSU swinger magnets for the new low background spectrometer is now in progress. Magnets have been temporarily remounted in the physics shop and the inter-magnet slits and pumping systems are under construction. The new installation will include a cryopump which has been ordered and a new gas target and beam diagnostics system. Motor drives and remote sensing interfaces have been ordered for computer controlled orientation of the swinger.

A contract has been awarded for the excavation and construction of the 30 meter tunnel which began on August 18, 1980. The optical alignment of the tunnel and the swinger axis will be accomplished using an interchangeable laser and telescope mounting system. The laser has been purchased and the integrated optical system will be installed at the time of the tunnel construction.

Modifications of the present high energy portion of the beam line will include the upgrading of the present doublet quadrupole to a triplet quadrupole system. Beam optics calculations have been performed for the new quadrupole triplet and swinger magnet configuration which indicate the system will transport the beam to targets at the expected locations. Requests for firm bids on the quadrupole triplet have been sent to four possible vendors.

Neutron detectors under consideration for the new low background facility include square glass envelopes using NE 213 scintillator liquid as well as the present circular envelopes used for the present detectors. The use of square detectors would allow optimum stacking multidetector arrays for large solid angles while maintaining superior pulse shape discrimination of NE 213 scintillation liquid.

F. Multiple Scattering (P.E. Koehler)

A new multiple scattering program has been written to correct our differential elastic and inelastic cross section measurements. The program is written in FORTRAN IV and runs on an IBM 370/158 computer. This new program follows the general outline of our previous code, MONTE SAMPLE, which is itself a modified version of a program received from A. Smith of Argonne (Sm 75). The new program, however, has several additional features which make it possible to compute corrections for differential cross sections to discrete inelastic groups as well as the elastic group.

Input to the program falls into two groups: (1) Energy-cross section libraries for the elastic and several inelastic groups, and (2) variables from the particular experimental arrangement. Output consists of correction factors, diagnostics, and a calculated time-of-flight spectrum for each of the several detector positions at a given energy. Each "neutron" in the program is tracked from the source, through the sample (for up to a maximum of 5 collisions), and once out of the sample then on to the various detector positions. Standard Monte-Carlo techniques are used throughout this tracking process.

There are several important features which enable the new program to produce much better results for the discrete inelastic groups of light nuclei than the older code MONTE SAMPLE. These include an energy-differential cross section library for each inelastic group to be corrected, a routine to introduce an energy spread into the incident neutron beam much like that encountered in a typical experiment, more flexibility in choosing the angular limits of the bins representing the detector positions, an output time-of-flight spectrum for each bin, and the use of equivalent volume-normalized spherical sample geometry rather than the true experimental right-circular cylindrical geometry.

The incident energy spread routine and the increased flexibility in choosing the angular size of the detector bins are very important features for light nuclei. These two options allow one to more accurately match the actual experimental situation in which the energy and time-of-flight spread of the various time-of-flight peaks changes from angle to angle and from one energy to another. These input parameters may be varied until the spectra produced by the program closely match those of the experiment. In this way, the same integration cursors used in the experiment may be used in the program. Once these input parameters are set at a single incident energy for a given nucleus and experimental arrangement, the same parameters may be used as input to the program for correcting data taken at several different incident energies.

The use of equivalent volume-normalized spherical sample geometry increases the simplicity of the programming and greatly decreases the amount of computer time needed to obtain statistically accurate results. This change from actual cylindrical experimental geometry to equivalent spherical geometry was carefully checked using a slower running code employing the true cylindrical experimental geometry. The increase in the statistical accuracy of the correction factors resulting from the much faster running time made possible by this change in geometries far outweighs any ill effects due to the approximation involved.

Figs. 33 through 36 show typical time-of-flight spectra calculated by the new program plotted along with the corresponding experimental spectra. The calculated spectra have been corrected for the change in efficiency with energy of the detector used in the experiment and have been normalized to the same number of total counts as is the experimental spectrum. The good agreement between these two sets of spectra show the quality of the results that have been obtained.

FIGURE 33 Comparison of experimental time-of-flight spectrum and spectrum calculated by our new multiple scattering program for ^{11}B at an incident energy of 4.81 MeV and a detector angle of 55 degrees. The calculated spectrum is represented by the Histogram.

FIGURE 34 Comparison of experimental time-of-flight spectrum and spectrum calculated by our new multiple scattering program for ^{11}B at an incident energy of 6.00 MeV and a detector angle of 55 degrees. The calculated spectrum is represented by the histogram.

FIGURE 35 Comparison of experimental time-of-flight spectrum and spectrum calculated by our new multiple scattering program for ^{10}B at an incident energy of 7.55 MeV and a detector angle of 90 degrees. The calculated spectrum is represented by a histogram.

FIGURE 36 Comparison of experimental time-of-flight spectrum and spectrum calculated by our new multiple scattering program for ^{10}B at an incident energy of 6.20 MeV and a detector angle of 72.5 degrees. The calculated spectrum is represented by a histogram.

Figs. 37, 38 and 39 are plots of uncorrected and corrected differential inelastic cross sections for the 2.12 MeV group of ^{11}B . Though the change in the integrated cross section is usually not very large, the change in the shape of each angular distribution is nevertheless important.

As of now, the program has only been used to correct the ^{11}B differential elastic and inelastic data with good results. It appears that some modifications to the energy-spread routine may be necessary in order to deal with more demanding circumstances such as measurements made with shorter flight paths, and cases where the time-of-flight peaks of two or more discrete groups are not fully resolved. These modifications are expected to be made in the near future.

FIGURE 37 Angular distributions for the multiple scattering corrected and uncorrected differential inelastic cross section for the 2.12 MeV first excited state of ^{11}B at an incident energy of 5.32 MeV. The lines through the data points are Legendre polynomial fits.

FIGURE 38 Angular distributions of the multiple scattering corrected and uncorrected differential inelastic cross section for the 2.12 MeV first excited state of ^{11}B at an incident energy of 5.45 MeV. The lines through the data points are Legendre polynomial fits.

FIGURE 39 Angular distributions of the multiple scattering corrected and uncorrected differential inelastic cross section for the 2.12 MeV first excited state of ^{11}B at an incident energy of 6.00 MeV. The lines through the data points are Legendre polynomial fits.

G. Neutron-Gamma Pulse Shape Discrimination (D.A. Resler)

The measurements of differential elastic and inelastic cross sections have resulted in much larger dynamic ranges than encountered in measurements of elastic cross sections only. The combination of deep inelastics and light nuclei result in large differences in the energies of scattered neutrons. For example, consider ^{11}B with an incident neutron energy of 6.40 MeV. At 20° the elastically scattered neutrons have an energy of 6.32 MeV. At 160° the neutrons of the second inelastic group ($Q = -4.55$ MeV) have an energy of only 0.87 MeV.

In these experiments neutron-gamma pulse shape discrimination (PSD) is mandatory to reduce background. The main neutron detector used for these cross section measurements is a $4\frac{1}{2}$ in. diameter by 2 in. thick NE 213 liquid scintillator coupled to an RCA 4522 photomultiplier tube. The method used here for n- γ pulse shape discrimination has been described in a previous progress report (C00-2490-9). PSD spectra from a recent experiment are shown in fig. 40. The spectra shown here were taken with the neutron detector placed directly in front of the neutron source during a set of relative efficiency measurements for the system. As such, the ratio of neutrons to gammas is larger than in an actual scattering experiment. Figs. 41 and 42 show typical n- γ PSD spectra during scattering measurements. For the spectra shown in these three figures the detector bias was set for 0.45 MeV neutrons and gains were set for a maximum neutron energy of 6.4 MeV. Very good separation of the neutron and gamma groups was obtained as can be seen in the figures.

To provide maximum structure information, measurements of deep inelastic scattering and inelastic cross sections near threshold are required. The very low detector bias necessary for these measurement demands very effective PSD techniques. Several improvements are underway to increase

NEUTRON - GAMMA PSD -- AUGUST 80
 ALPHA = 0.0 XMIN = 0.90E 00 XMAX = 0.64E 01
 BETA = 45.00 YMIN = 0.70E 03 YMAX = 0.90E 03
 GAMMA = 185.00 ZMIN = 0.0 ZMAX = 0.34E-01

Figure 40 Neutron-gamma pulse shape discrimination taken during relative efficiency measurements for our latest run.

Figure 41 Typical pulse shape discrimination spectrum. For this case the sample was ^{11}B with an incident neutron energy of 6.4 MeV and a detector angle of 72.5 degrees. The neutron detector bias was about 450 keV.

Figure 42 Gated and ungated PSD spectra. Same conditions as described in figure 41. The conversion gains for the two spectra are slightly different,

the dynamic range of our PSD system and to make possible these more difficult experiments. New 8854 photomultiplier tubes have been purchased. These will replace the 4522 tubes now used on the detectors. The more sensitive photocathodes of the 8854 tubes should improve our PSD capabilities. Commercial tube bases and amplifiers have normally been used for PSD. New bases and amplifiers for better PSD are currently being built at this laboratory. The new PSD system--detectors and electronics--should be ready for testing this fall.

H. Scientific Publications, Papers Presented and Colloquia

A paper entitled "States in ^{12}B from Measurement and R-Matrix Analysis of $\sigma(\theta)$ for $^{11}\text{B}(n,n)^{11}\text{B}$ " was published in Nuclear Physics A340 (1980) 13, R.M. White, R.O. Lane, H.D. Knox and J.M. Cox. The following is the abstract of that paper:

ABSTRACT: Differential cross sections for neutrons elastically scattered from ^{11}B have been measured for 85 incident neutron energies for $2.6 \leq E_n \leq 8.0$ MeV corresponding to excitation energies in ^{12}B of 5.7 to 10.7 MeV. The cross sections were measured at nine laboratory angles per energy from 20° and 160° and show considerable resonance structure. These data, along with previously measured low-energy cross sections, have been analyzed for $0.1 \leq E_n \leq 7.0$ MeV with a multilevel-multichannel R-matrix program to make new assignments to states in ^{12}B . The R-matrix calculation allows for change of ℓ -values and for input in either j-j or L-S coupling schemes. A very good overall fit to the data is obtained over this wide range of excitation in ^{12}B . Comparisons with existing theoretical work are discussed.

A paper entitled "States in ^8Li from an R-Matrix Analysis of $^7\text{Li}(n,n)^7\text{Li}$ and $^7\text{Li}(n,n')^7\text{Li}^*(0.478, 4.63)$ Measurements," H.D. Knox and R.O. Lane, has been submitted for publication in Nuclear Physics. The following is the abstract of that paper:

ABSTRACT: A comprehensive multilevel multichannel R-matrix analysis of $^7\text{Li}+n$ scattering data has been completed. All available neutron elastic scattering and inelastic scattering data to the first two excited states of ^7Li up to 8 MeV incident neutron energy were included in the analysis. Good overall fits to all cross section data throughout this energy range were obtained. In this study six previously unknown levels in ^8Li have been identified and spin and parity assignments for these and all previously identified levels in ^8Li except the very narrow one at $E_x = 6.53$ MeV have been made. The present results are in excellent agreement with previous analysis and model calculations.

A paper entitled "An R-Matrix Analysis of the ${}^7\text{Li}+n$ System," H.D. Knox and R.O. Lane was presented at the Knoxville Meeting of the Division of Nuclear Physics of the American Physical Society, October 18-20, 1979. The abstract for this paper was given in the progress report for last year.

Three papers were presented at the International Conference on Nuclear Cross Sections for Technology, October 22-26, 1979. Abstracts for these papers were given in the progress report for last year.

Study of Neutron-Induced Charged Particle Reactions on Deuterium Using Quadrupole Triplet Spectrometer. V. Kulkarni, S.M. Grimes, P. Grabmayr, G. Randers-Pehrson, R. Finlay and J. Rapaport, Ohio University

A Study of Source Neutron Reactions. P. Grabmayr, J. Rapaport, S.M. Grimes, R.W. Finlay and V. Kulkarni, Ohio University

R-Matrix Analysis of Neutron Elastic and Inelastic Scattering Data. H.D. Knox, R.O. Lane, D.A. Resler and P.E. Koehler, Ohio University

The following is an abstract of a paper presented at the Washington, D.C. Meeting of the American Physical Society, April 28 - May 1, 1980.

ABSTRACT: Soft Sphere R-Matrix Fit to Alpha-Alpha Scattering. G. Randers-Pehrson*, Ohio University--Alpha-alpha elastic phase shifts have been described using R-matrix theory with background terms derived from a soft repulsive potential. Reduced widths for some closed channels are also included. Some aspects of R-matrix description of broad final states will also be discussed. No levels except the obvious ones are needed.

* Work based on a dissertation presented to the University of Maryland.

The following two abstracts have been submitted to the Seventh Symposium on Microdosimetry, September 1980, Oxford, United Kingdom.

ABSTRACT: Energy Spectra and Cross Sections for Charged Particles Produced by 24 MeV Neutrons on Carbon. R.W. Finlay, P. Grabmayr, J. Rapaport and G. Randers-Pehrson, Ohio University--In order to calculate slowing-down spectra, cavity energy deposition spectra, kerma and other quantities of importance in neutron dosimetry, it is essential that initial spectra of charged particles produced by neutrons incident on tissue-constituent nuclei be well understood. Direct measurements of the initial spectra or of the relevant microscopic cross sections are generally unavailable for $E_n > 20$ MeV. To measure these spectra, a large-solid-angle (10 msr) magnetic quadrupole triplet spectrometer has been constructed and employed in a manner similar to the traditional charged-particle recoil telescope. The magnetic spectrometer has the important advantage over conventional telescopes that the charged particle detector can be placed in a region of lower background far away from the neutron source without sacrificing the solid angle of the instrument. The magnetic lens system has rather poor resolution $\frac{\Delta E}{E} \sim 30\%$; energy resolution is regained by using a suitable particle detector at the focal point. Pulsed beams of nearly mono-energetic neutrons are produced in the energy region from 20 to 26 MeV by means of the $^3\text{H}(d,n)^4\text{He}$ reactions with deuteron beams obtained from the Ohio University high current tandem Van de Graaff accelerator. Neutrons impinge on thin carbon foils located at the object point of the magnetic quadrupole lens system. Emerging charged particles are transported to a two-element charged particle telescope 3.4 m away from the target foil. A two-element telescope is used to reduce background events caused by neutron-induced reactions in the vicinity of the detector. Unambiguous mass-identification of the reaction products is accomplished by measuring charged-particle time-of-flight and calculating the product $E(T_0 - T)^2$ cm in the data-acquisition computer. Silicon surface barrier detectors, intrinsic germanium detectors and gas proportional counters are used as particle detectors depending on the range and linear energy transfer of the particles being detected. Absolute normalization of the measured energy spectrum is obtained by replacing the target foil by a thick hydrogenous radiator such as polyethylene.

The realizable energy resolution of the spectrometer is determined by the properties of the neutron production reaction and the resolution of the particle telescope but not by the optical properties of the magnetic lens system. The spectrometer can be used for the study of transitions to discrete final states, e.g. $^{12}\text{C}(n, \alpha_0)^9\text{Be}_{\text{g.s.}}$ or the multiparticle-breakup reactions such as $^{12}\text{C}(n, n')^3\alpha$. Data on both of these processes will be presented, and the prospects for additional measurements of interest in microdosimetry will be discussed.

ABSTRACT: Microdosimetric Measurements in 8, 20 and 25 MeV Neutron Fields. Joseph C. McDonald*, R.W. Finlay, P. Grabmayr and G. Randers-Pehrson, Ohio University--Measurements of the event-size distribution in lineal energy were carried out in nearly monoenergetic neutron fields whose principal energy were 8, 20 and 25 MeV. The commercially produced spherical A-150 plastic walled proportional counter employed (E.G.&G. LET- $\frac{1}{2}$) was filled to a pressure of approximately 33 Torr with propane-based tissue equivalent gas, thereby simulating an effective counter diameter of approximately 1 μm . Neutrons were produced by bombarding a small tritium gas cell with 9.0 MeV protons, 3.95 MeV and 8.11 MeV deuterons, yielding approximately 8, 20 and 25 MeV neutrons, respectively. The neutron energy spectra were measured using conventional time-of-flight techniques which have been described in detail elsewhere (1). In order to determine the fraction of low energy neutrons generated by charged particle interactions, other than with tritium, in the target cell, a spectrum was measured using an empty target. The fraction of gamma-rays present in these neutron fields was estimated from the time-of-flight spectra and the dose due to events below about 20 $\text{keV} \cdot \mu\text{m}^{-1}$ recorded by the proportional counter. The event-size distribution measured for 20 MeV neutrons compares favorably with recent theoretical calculations (2), and the value of $\bar{y}_D$ for this energy was found to be approximately 110 $\text{keV} \cdot \mu\text{m}^{-1}$, which can be compared to the value computed for the theoretical distribution of 125 $\text{keV} \cdot \mu\text{m}^{-1}$, assuming a 1 μm effective site diameter. In addition, the measured distribution revealed more detail in the region from 100 to 500 $\text{keV} \cdot \mu\text{m}^{-1}$, where the proton and alpha edges are clearly visible and distinct.

Some corrections are being made to the 8 and 25 MeV data in order to account for the presence of low energy, target generated, neutrons. It is estimated that the uncertainty in these measurements is approximately $\pm 10\%$, primarily due to the assumption of a single value of W for the entire event-size distribution. This is obviously an oversimplification, and it is possible that theoretical calculations may be capable of taking into account the different ionization yields from the charged particles producing events in an actual counter. The present measurements provide data for several high energy monoenergetic neutron fields which have not previously been investigated to date. Further comparisons of measurements and theoretical calculations in this energy range should provide valuable cross checks for both approaches.

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The following abstract has been submitted to the Minneapolis Meeting of the American Physical Society, October 9 - 11, 1980.

ABSTRACT: Neutron-Induced Charged Particle Reactions on Deuterium.

V. Kulkarni, J. Rapaport, R.D. Koshel, R.W. Finlay, G. Randers-Pehrson and P. Grabmayr, Ohio University--The reaction ${}^2\text{H}(n,p){}^2\text{n}$ has been investigated at incident $E_n = 11$ and 25 MeV with good energy resolution using the Ohio University quadrupole triplet spectrometer. The ${}^2\text{H}(n,d)n$ elastic scattering angular distribution has also been measured at $E_n = 9$ and 11 MeV. Theoretical calculations of deuteron break-up and elastic scattering cross sections have been performed on the basis of Faddeev three-body formalism and separable two-body interactions. The experimental cross sections will be compared with predictions of theoretical analysis. Comparisons with previous break-up data (1) at $E_n = 14$ MeV will also be presented.

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A colloquium entitled "Structure Studies of Light Nuclei with Neutrons" was presented at Lawrence Livermore National Laboratory by R.O. Lane on July 9, 1980.

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