STUDY OF STRUCTURE OF NUCLEI WITH NEUTRONS

and

NUCLEAR DATA MEASUREMENTS FOR MFE

Progress Report

MASTER

Raymond O. Lane

Ohio University

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ABSTRACT

Measurements of neutron inelastic scattering cross sections for ${}^7\text{Li}(n,n'){}^7\text{Li}^*$ (0.478 MeV) made at this Laboratory together with our earlier elastic scattering results have been analyzed in terms of our new multilevel-multichannel R-Matrix calculation. The investigation has led to the assignment of many more levels in ${}^8\text{Li}$ than were previously known with confidence. These results are in good agreement with recent theoretical model calculations, so that together the two provide considerable advancement in the state of our knowledge of ${}^8\text{Li}$, the knowledge of which has stood virtually motionless for two decades. Inelastic differential cross sections have been measured from 4.8 to 6.5 MeV for ${}^{11}\text{B}$ and ${}^{13}\text{C}$ over part of the resonance region of each nucleus. These form the initial portion of a comprehensive study of the compound nuclei ${}^{12}\text{B}$ and ${}^{14}\text{C}$ using inelastic and elastic data in a multichannel-multilevel R-Matrix analysis. The construction and optimization testing of the triplet quadrupole spectrometer for study of (n,z) reactions are essentially completed. Performance tests show that design characteristics of solid angle and resolution have been achieved. Initial measurements with the spectrometer to study the neutron-neutron final state interactions in the $\text{D}(n,p)nn$ reaction at $E_n = 9$ and 11 MeV, and measurements of the elastic scattering of neutrons by deuterium by observation of the recoil deuterons with the spectrometer is now underway. These results are preliminary to the (n,z) measurements on structural and tritium-breeding elements of fusion reactor designs.

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INTRODUCTION

In the year since the last progress report we have performed much of the proposed inelastic scattering program and have made very good progress in bringing on-line the triplet quadrupole spectrometer.

In our quest to learn more of the structure of the light nuclei our R-matrix analysis of our data on elastic scattering revealed structure not previously known in several light nuclei. It also pointed to the need for inelastic scattering differential cross sections at these same energies so that a more complete R-matrix analysis of data in all available open channels could be made, thus leading to more unique energy-level assignments to the rather complex level structure at these energies. We have begun this program of inelastic differential cross sections and report here results to date on the scattering nuclei ${}^7\text{Li}$, ${}^{11}\text{B}$ and ${}^{13}\text{C}$. Prior to our measurements virtually no previous inelastic data of any extent or suitable accuracy existed in this energy region that would permit a study of the structure of these nuclei, or in fact for hardly any of the light nuclei in this mass region. To analyze our inelastic together with our elastic data we have written an expanded version of our R-matrix analysis program to include inelastic channels. This was necessitated since R-matrix computer programs suitable for our problem and our computer were not available. In fact, a literature search has so far revealed no such previous analysis or experimental endeavor to use elastic together with the inelastic channels to study the structure of the light nuclei. The R-matrix formalism is an exact, rigorous and complete formalism within which we can analyze our experimental results in terms of parameters which can be related to basic nuclear models. However, the R-matrix itself says nothing as to what these

often numerous parameters should be, but rather we must assume various values and by trial and error see what fits the data. This is time consuming and, in many-parameter space, usually contains some degree of ambiguity among the parameters giving the best fit to the data. The best approach would be to do basic nuclear model calculations that would predict the elastic and inelastic scattering cross sections directly for comparison to experiment. The very few such relevant calculations that do exist in this mass region will be mentioned in the report. Since all of these have various simplifying assumptions together with a limited degree of applicability to our data, we have initiated two modest theoretical efforts of our own to glean more knowledge of the basic model structure of these light nuclei. One is the applicability to our data of the core-coupling model based on the harmonic oscillator. This was more readily available but is essentially a bound-state calculation. The second is a more realistic continuum-shell-model calculation interpreted in terms of the R-matrix parameters which allows immediate and direct comparison to our data. The framework of the initial phase of this calculation was resurrected from a related application at another laboratory and progress in documentation and initial test calculations relevant to our data will be described. These investigations in the light nuclei provide data and model information pertinent to the needs of the Magnetic Fusion Energy program and form part of our program commitments to MFE needs described in the report.

The new portion of the contract includes the construction of a unique triplet quadrupole spectrometer to study the double-differential cross sections for production of charged particles, primarily protons, deuterons, alphas, tritons and helions, in the (n, z) reactions on various nuclei.

Emphasis is given to those nuclides comprising structural, shielding, and tritium-breeding members of fusion reactor designs. The spectrometer proper has been constructed and test results will be described in the report. Modifications of various components have been made to achieve optimum performance. Except at the singular energy of 14 MeV, little if any differential (n,z) cross sections with respect to angle and/or energy exist in the energy range of $\sim 8 - 40$ MeV. The need for these cross sections is now even more important since approval has been given for the construction of the Fusion Materials Irradiation Test facility (FMIT) which will test fusion reactor components at neutron energies up to ~ 40 MeV or so. The Ohio University Tandem Accelerator has an almost unique capability of providing a very high intensity pulsed (or d.c.) beam which enables our Laboratory to perform these difficult (n,z) measurements over a substantial and important part of that energy range. The first series of measurements of (n,z) differential cross sections is now underway and preliminary results from them are described in the report.

II. Differential Inelastic and Elastic Scattering Cross Sections. (H. Knox)

A. ${}^7\text{Li}(n,n'){}^7\text{Li}^*(0.478)$ and ${}^7\text{Li}(n,n){}^7\text{Li}$ Data and the R-Matrix Analyses of the ${}^8\text{Li}$ System

Our work with studies of elastic and inelastic scattering of neutrons from ${}^7\text{Li}$ is well ahead of our planned schedule outlined at the coordination meeting for the MFE program held at TUNL March 5 - 6, 1979. In our proposed schedule we were to add the capability for calculating inelastic cross sections to our R-matrix analysis program and to begin the R-matrix analysis of the ${}^7\text{Li} + n$ system. Both of these goals have been attained and the analysis is almost completed -- a goal that was originally set for FY-80. The results of this work will be described in two parts, first a description of the new R-matrix program and second a summary of the results of an R-matrix analysis of available ${}^7\text{Li} + n$ elastic and inelastic scattering data.

1. An R-Matrix Analysis Program for the Study of Elastic and Inelastic Neutron Scattering Data

The study of both elastic and inelastic neutron scattering for the light nuclei has many important applications in the nuclear energy and neutron standards programs as well as providing important information to theorists doing nuclear structure calculations. A computer code for performing R-matrix analyses of elastic and inelastic neutron scattering data has recently been completed. The program operates on an IBM 370 computer and a Tektronix 4025/4631 graphics terminal provides visual display of both experimental data and calculated fits to the data.

The program is a multichannel-multilevel calculation which can be used for the analysis of elastic and inelastic neutron scattering data

to the first two excited states of the target nucleus. The experimental data to be fit, are in the form of Legendre polynomial expansion coefficients. Typical data are shown in Figure 1 for ${}^7\text{Li} + n$ scattering. The program can calculate up to five expansion coefficients for up to two hundred incident neutron energies for each of the three particle (i.e. elastic and inelastic) channels.

For ease of comparison of the results of this type of analysis with model calculations, it is desirable to have the option of performing the R-matrix analysis in either the channel coupling or j-j coupling schemes. This option is included in the program as discussed below.

For each of the three particle channels allowed in the program, four angular momentum channels and up to five levels of the same total angular momentum and parity (J^π) are allowed. Orbital angular momentum values up to and including $\ell = 3$ are permitted. Typical input data for a given J^π are shown in Figure 2. These data include:

1. Number of angular momentum channels for each of the three particle channels.
2. Number of levels for this J^π .
3. ℓ value for each channel.
4. Channel spin, S , for each channel (for calculation using channel coupling).
5. j-values for each channel (for calculations using j-j coupling).
6. Level energy, E_λ , and reduced widths, γ_{cc} , for each level.
7. Constant background R_0 terms. The R_0 matrix is symmetric and only half of it appears as input.

Figure 1. Legendre polynomial expansion coefficients used as input for the R-matrix program. These coefficients are for elastic neutron scattering from ^7Li . Abscissa on this and following figures is bombarding energy in MeV. Increasing order of B_L goes from bottom to top.

JPI 2 -							
CHAN	1	2	3	4	5	6	7
L	0	2	2	2	2	2	2
S	2	1	2	1	0	3	4
J	0.5	1.5	2.5	2.5	1.5	1.5	2.5
LEV1	6.0	1.1	0.0	0.0	0.0	0.0	1.0
LEV2	2.0	2.5	0.0	0.0	2.0	0.0	0.0
1	0.3						
2	0.0	0.1					
3	0.0	0.0	0.1				
4	0.0	0.0	0.0	0.1			
5	0.0	0.0	0.0	0.0	0.1		
6	0.0	0.0	0.0	0.0	0.0	0.1	
7	0.0	0.0	0.0	0.0	0.0	0.0	0.1
BC	0.0	-1.07	-1.07	-1.17	-1.17	-2.26	-2.26

Figure 2. Typical input for the program. For ${}^7\text{Li} + n$, there are a total of 7 channels open, three elastic and two each for each of the inelastic channels for $J^\pi = 2^-$. The input is explained in more detail in the text.

8. Boundary conditions for each channel.

The program uses a format free assembler-read routine with an analysis of the input data to detect possible errors in the numerous input parameters.

To actually calculate the B_L coefficients from the scattering matrix, the equations given by Blatt and Biedenhain (Bl 52) are used in this program. These equations assume the use of the channel coupling scheme. If j-j coupling is to be used in the R-matrix calculation, a transformation from j-j to the channel coupling scheme must be made at some point in the calculation prior to computation of the Legendre coefficients. In general two options exist. First, the reduced widths and background R_0 inputted in the j-j scheme could be immediately transformed to the channel coupling scheme and the entire calculation completed in the latter scheme. Second the calculation could be carried out in j-j coupling up to computation of the scattering matrices and these then transformed to the channel coupling scheme before the B_L coefficients are calculated. If the B_L coefficients are to be calculated at several energies for a given set of input parameters, the first option is more efficient since it involves only one set of transformations whereas the second method involves a transformation for each J^π at each energy. The first method is used in the present program. The reduced widths transform from j-j to channel coupling according to the formula:

$$\gamma_{\lambda(\alpha s l)}^J = \sum_{j=l+1/2} (2s+1)^{1/2} (2j+1)^{1/2} W(\frac{1}{2}I_{\alpha_2} J l, s j) \gamma_{\lambda(\alpha, j, I_{\alpha_2})}^J$$

where $(\alpha j I_{\alpha_2})$ refers to the j-j coupling scheme, $(\alpha s l)$ refers to the channel coupling scheme and the $W(\frac{1}{2}I_{\alpha_2} J l, s j)$ are Racah coefficients.

The background R_0 's transform as follows:

$$R_{(\alpha s \ell, \alpha' s' \ell')}^{L-S} = \sum_{j=\ell \pm \frac{1}{2}} \sum_{j'=\ell' \pm \frac{1}{2}} (2s+1)^{\frac{1}{2}} (2j+1)^{\frac{1}{2}} W(\frac{1}{2} I_{\alpha_2} J \ell, s j) R_{(\alpha j I_{\alpha_2}, \alpha' j' I'_{\alpha_2})}^{j-j} \\ \times (2s'+1) (2j'+1) W(\frac{1}{2} I'_{\alpha_2} J \ell', s' j')$$

A simplified flow diagram of the operation of the program is given in Figure 3. After reading in the input parameters, the transformation to channel-coupling is made if necessary. For each energy the surface functions S_ℓ , P_ℓ and ϕ_ℓ are calculated. Then for each J^π , the R-matrix is formulated according to

$$R_{c'c}^{J^\pi} = \left\{ \sum_{\lambda=1}^{N \leq 5} \frac{\gamma_{\lambda c'} \gamma_{\lambda c}}{E_\lambda - E} + R_{0c'c} \right\} J^\pi.$$

Next the scattering matrix is computed for each J^π from

$$S^{J^\pi} = \Omega (1 + 2iP^{\frac{1}{2}} (1 - R^{J^\pi} L_0)^{-1} R^{J^\pi} P^{\frac{1}{2}}) \Omega$$

Finally for each of the three particle channels, the B_L coefficients are calculated for that energy using

$$B_L(\alpha' s', \alpha s) = \frac{(-1)^{s'-s}}{4} \sum_{J_1} \sum_{J_2} \sum_{\ell_1} \sum_{\ell_2} \sum_{\ell'_1} \sum_{\ell'_2} \times Z(\ell_1 J_1 \ell_2 J_2, s L) Z(\ell'_1 J_1 \ell'_2 J_2, s' L) \\ \times R.P. [(\delta_{\alpha' \alpha} \delta_{s' s} \delta_{\ell'_1 \ell_1} - S_{\alpha' s' \ell'_1; \alpha s \ell_1}^{J_1})^* \times (\delta_{\alpha' \alpha} \delta_{s' s} \delta_{\ell'_2 \ell_2} - S_{\alpha' s' \ell'_2; \alpha s \ell_2}^{J_2})].$$

The three files consisting of the calculated B_L coefficients as functions of energy for each of the particle channels are then transferred to the Tektronix 4025/4631 graphics terminal. Here plots of experimental

Figure 3. Simplified block diagram of the R-matrix program.

data and calculated fits to the data are made. An example of this output is shown in Figure 4.

At present the program takes approximately 30 seconds of IBM 370 CPU time for computation of the three sets of B coefficients at one energy. Work will continue to speed up the execution of the program. It is planned to add charged particle channels to the calculation at a later date.

2. An R-Matrix Analysis of the ${}^7\text{Li} + n$ System

The study of neutron scattering from ${}^7\text{Li}$ has important applications since lithium is to be used in the breeding blankets of proposed fusion reactors. Possible reactions of neutrons with ${}^7\text{Li}$ are shown in Table 1 for neutron energies up to 8 MeV. The first excited state of ${}^7\text{Li}$ decays by γ -emission (0.478 MeV) and because of the relatively smooth energy variation of the cross section (Figure 5) it has been suggested that this reaction could be used as a standard for other gamma producing reactions if the cross section were known to sufficient accuracy. All other reactions below 8 MeV are particle unstable and ultimately result in a triton being emitted. Though tritium production cross sections have been measured, these individual reactions have not been studied separately with one notable exception -- below 8 MeV determinations of the ${}^7\text{Li}(n,n'){}^7\text{Li}^*$ ($Q = 4.63$ MeV) cross section have been made at one energy by Hopkins et al (HO 68) and at two energies by Batchelor and Towle (BA 63). Recently measurements for $8.5 \leq E_n \leq 14$ MeV have been completed at TUNL (HO 79) on this reaction cross section.

An energy level diagram (Aj 79) for the ${}^8\text{Li}$ system is shown in Figure 6. Except for the bound levels and the 3^+ level at $E_x = 2.26$ MeV,

Figure 4. Example of graphic output from R-matrix calculation.

TABLE 1
POSSIBLE ${}^7\text{Li} + \text{N}$ REACTIONS

<u>Reactions</u>	<u>Q-Value (MeV)</u>	<u>Threshold (MeV)</u>
1. ${}^7\text{Li}(\text{n},\text{n}){}^7\text{Li}$	0.0	0.0
2. ${}^7\text{Li}(\text{n},\text{n}'){}^7\text{Li}^* \rightarrow {}^7\text{Li} + \gamma$	-0.478	0.547
3. ${}^7\text{Li}(\text{n},\text{tn}')\alpha$	-2.467	2.821
4. ${}^7\text{Li}(\text{n},\text{t}){}^5\text{He} \rightarrow \alpha + \text{n}'$	-3.423	3.915
5. ${}^7\text{Li}(\text{n},\text{n}'){}^7\text{Li}^* \rightarrow \alpha + \text{t}$	-4.633	5.298

Figure 5. Gamma ray yield at 145° for the ${}^7\text{Li}(n,n'\gamma){}^7\text{Li}$ (0.478 MeV) reaction.

Figure 6. Energy level diagram for ^8Li .

the spins and parities of levels in ^8Li are unknown. The total cross section for $^7\text{Li} + n$ shown in Figure 7 shows very little structure except that due to the 3^+ level mentioned earlier. The cross section for inelastic scattering to the first excited state (Figure 5) also shows little structure. Three peaks in this cross section are seen near 1 MeV, 3.3 MeV and a slight indication of one near 5.8 MeV incident neutron energy.

The number of analyses of data in regions other than that of the known 3^+ level is exceedingly small. Lane et al (LA 64) analyzed neutron scattering and polarization data up to about 2 MeV incident energy. Other than the 3^+ level at 2.26 MeV excitation energy no other definite assignments were made though there were indications of broad 2^- and 3^- levels present.

Freeman et al (FR 55) analyzed low energy inelastic data and found good agreement between experiment and calculation was obtained if the level at $E_x = 3.21$ MeV was assumed to be 1^+ with a 1^- ($\ell = 0$) background present. They could not, however, eliminate the possibilities that this state might be either a 1^- or 2^- .

Presser and Bass (PR 72) have performed an analysis of 478 KeV gamma ray production data in the region $2.0 \text{ MeV} \leq E_n \leq 8.0 \text{ MeV}$. The two peaks near $E_n = 3.3 \text{ MeV}$ and 5.8 MeV were determined to have $J = 2, 3, \text{ or } 4$ and $J = 3 \text{ or } 4$ respectively. Best fits to the data were obtained when the two levels were assumed to be $J^\pi = 2^+$ and 3^+ respectively.

The only recent detailed model calculations for the $^7\text{Li} + n$ system are multichannel cluster model calculations by Stowe and Zahn (ST 77). Both a scattering calculation and a bound and quasibound state calculation

Figure 7. Total neutron cross section for ${}^7\text{Li} + n$.

were performed. The results of these calculations are shown in Figure 8. In addition to the known 3^+ level, these results showed 0^+ , 1^+ , 1^- and 2^- states near the ${}^7\text{Li}^* - n$ threshold and broad 3^- and 4^- states near the ${}^3\text{He}^* - t$ threshold. Though more levels were predicted in this study than are presently known, the spins and parities of the predicted levels are in agreement with the previously mentioned analyses -- i.e. the 1^+ favored by Freeman et al (FR 55), the 2^- and 3^- indicated by Lane et al (LA 64) and $J = 2, 3$ or 4 predicted by Presser and Bass (PR 72). In addition, work by Barker (BA 77) has predicted a 2^- state near 2.5 MeV.

Work at this Laboratory in the last few years has provided a large amount of neutron scattering data for ${}^7\text{Li} + n$. Our recently published ${}^7\text{Li}(n, n_0 + n_1){}^7\text{Li}$ data for $4 \text{ MeV} \leq E_n \leq 7.5 \text{ MeV}$ provide the first detailed set of scattering data in this energy region. We are currently analyzing elastic and inelastic scattering data for the energy region $2 \text{ MeV} \leq E_n \leq 4 \text{ MeV}$. These data, the earlier work by Lane et al (LA 64) for $0 \text{ MeV} \leq E_n \leq 2 \text{ MeV}$, the inelastic work of Knitter and Coppola (KN 68) for $1.12 \text{ MeV} \leq E_n \leq 2.30 \text{ MeV}$ and the work of Hopkins et al (HO 68) and Batchelor and Towle (BA 63), provide a large data base for which an R-matrix analysis of the ${}^7\text{Li} + n$ system can be undertaken. The Legendre polynomial expansion coefficients for ${}^7\text{Li} + n$ "elastic" scattering for $0 \text{ MeV} \leq E_n \leq 8 \text{ MeV}$ are shown in Figure 9. The data from $2 \text{ MeV} \leq E_n \leq 4 \text{ MeV}$ are actually the only pure elastic scattering data; all remaining data are ${}^7\text{Li}(n, n_0 + n_1){}^7\text{Li}$. For these data the B_0 term for each data point has been reduced by an amount $\sigma_{\text{inel}}/4\pi$ where the integrated cross sections, σ_{inel} , were obtained from the work of Dickens and Love (DI 74). The remaining B_L coefficients i.e. ($L = 1$ through 4) are actually sums of

Figure 8. Level scheme for ${}^8\text{Li}$ from the cluster model calculations by Stowe and Zahn (ST 77). (a) Results of a scattering calculation, (b) results of a bound and quasibound state calculation (c) experimental results from (AJ 79).

Figure 9. Legendre polynomial expansion coefficients for elastic scattering of neutrons from ${}^7\text{Li}$.

$B_L(\text{elastic}) + B_L(\text{inelastic})$. However, the expansion coefficients for the inelastic group tend to be roughly an order of magnitude smaller than the B_L coefficients for the elastics. The expansion coefficients for the ${}^7\text{Li}(n,n'){}^7\text{Li}^*$ (0.478 MeV) reaction are shown in Figure 10. At low energies the data of Knitter (KN 68) are used and at higher energies, the data displayed are the results of a curve fitting calculation on our ${}^7\text{Li}(n,n_0+n_1){}^7\text{Li}$ data for $4 \text{ MeV} \leq E_n \leq 7.5 \text{ MeV}$ as described in an earlier progress report (LA 76). These data along with those of Hopkins et al (HO 68) provide a data base for the study of the inelastic cross section for scattering to the first excited state of ${}^7\text{Li}$. Finally the only available data for inelastic scattering to the second excited state of ${}^7\text{Li}$, $Q = -4.63 \text{ MeV}$ below 8 MeV incident neutron energy are shown in Figure 11. These include one point $E_n = 7.54 \text{ MeV}$ by Hopkins et al (HO 68) and at two points $E_n = 6.36 \text{ MeV}$ and 7.5 MeV by Batchelor and Towle (BA 63).

Using the program described in the last section an analysis of these elastic and inelastic data have been undertaken. For this study the channel radii for the elastic and inelastic channels were assumed to be 4.3 F. For each ℓ , the boundary conditions were chosen to be equal to the shift functions, S_ℓ , evaluated at 4 MeV i.e. in the middle of the energy region under study. A short summary of the spins and parities of levels considered in this study is given Table 2. A listing of the total input for the calculation is given at the end of this section. The preliminary fits to the elastic, first inelastic and second inelastic cross sections are given in Figures 12, 13, 14.

In the energy region up to 8 MeV, ten levels are needed to fit the ${}^4\text{Li} + n$ data. In order of increasing excitation energy, these levels

Figure 10. Legendre polynomial expansion coefficients for inelastic (0.478 MeV) scattering of neutrons from ^7Li .

Figure 11. Legendre polynomial expansion coefficient for inelastic (4.63 MeV) scattering of neutrons from ${}^7\text{Li}$.

TABLE 2

J^π	E_λ		Elastic				First Inelastic		Second Inelastic			
0^+	2.3	L S BC γ	1 1 -0.27 0.7				1 1 -0.3 0.0		3 3 -3.2 0.0			
1^+	0.7	L S BC γ	1 1 -0.27 0.6	1 2 -0.27 1.1	3 2 -2.3 0.0		1 0 -0.3 0.6	1 1 -0.3 0.6	3 3 -3.2 0.0	3 4 -3.2 0.0		
1^-	5.8 2.5	L S BC γ γ	0 1 0.0 0.4 0.0	2 1 -1.1 0.8 1.5	2 2 -1.1 0.0 0.0		0 1 0.0 -0.2 0.0	2 1 -1.2 -0.2 0.0	2 3 -2.3 1.0 0.0			
2^+	8.0	L S BC γ	1 1 -0.27 2.4	1 2 -0.27 0.0	3 1 -2.3 0.0	3 2 -2.3 0.0	1 1 -0.3 1.0	3 1 -2.4 0.0	1 3 -1.5 -1.0	3 3 -3.2 0.0	3 4 -3.2 0.0	
2^-	2.0 6.8	L S BC γ γ	0 2 0.0 2.5 1.1	2 1 -1.1 0.0 0.0	2 2 -1.1 0.0 0.0		2 1 -1.2 2.0 0.0	2 0 -1.2 0.0 0.0	2 3 -2.3 0.0 0.7	2 4 -2.3 0.0 0.7		
3^+	0.12	L S BC γ	1 2 -0.3 0.5	3 1 -2.3 0.0	3 2 -2.3 0.0		3 0 -2.4 0.0	3 1 -2.4 0.0	1 3 -1.5 0.0	1 4 -1.5 0.0	3 3 -3.2 0.0	3 4 -3.2 0.0
3^-	3.3	L S BC γ	2 1 -1.1 1.0	2 2 -1.1 1.0			2 1 -1.2 1.0		0 3 -0.9 0.0	2 3 -2.3 0.0	2 4 -2.3 0.0	
4^-	4.0	L S BC γ	2 2 -1.1 1.1						0 4 -0.9 0.0	2 3 -2.3 0.0	2 4 -2.3 0.0

Figure 12. Preliminary results of R-matrix calculation for neutron elastic scattering from ^7Li .

Figure 13. Preliminary results of R-matrix calculation for neutron inelastic scattering from the 0.478 MeV level of ^7Li .

Figure 14. Preliminary results of R-matrix calculation for neutron inelastic scattering from the 4.63 MeV level of ${}^7\text{Li}$.

are first the 3^+ at $E_n = 0.261$, next a 1^+ state dominating the low energy portion of the first inelastic cross section corresponding to $E_x = 3.21$ MeV. In the region from 1.5 to about 3 MeV are three broad levels 0^+ , 1^- and 2^- . The first inelastic cross section is unaffected by the 0^+ and 1^- but the elastic cross section is affected by all three. Between 3 and 4.5 MeV are a 3^- and a 4^- state. The 3^- ($E_x = 5.4$ MeV) is responsible for the peak in the inelastic at 3.3 MeV. The 4^- state ($E_x = 6.1$ MeV) dominates the broad peak in the elastic cross section near $E_n = 4.6$ MeV. Between 5 and 7 MeV there are again broad 1^- and 2^- states. The 1^- is responsible for the "peak" in the first inelastic cross section at 5.8 MeV while the 2^- is responsible for the broad peak in the elastic at $E_n = 6.3$ MeV. Finally a broad 2^+ state is predicted at $E_n \approx 8$ MeV. This state is probably the least certain of those reported here. The recent TUNL data for the ${}^7\text{Li}(n,n'){}^7\text{Li}^*$ ($Q = -4.63$ MeV) cross section show dominant B_1 terms. This implies an interference between positive and negative parity states. With the 1^- and 2^- states near 6 MeV a broad positive parity state must be present. Inclusion of the 2^+ state generally improved overall fits particularly B_3 and B_4 .

The agreement between the levels predicted for the ${}^8\text{Li}$ compound nucleus from the present work with those predicted in the work by Stowe and Zahn (ST 77) is remarkably good. All levels predicted by the latter except the 0^- which appeared only in the bound and quasibound calculation appear in the present study. More surprising, the energies at which these levels occur are in good agreement in the two analyses. Further calculations are presently underway to determine if these spin and parity assignments are unique. Table 3 lists the complete preliminary set of parameters for the fits shown in this report.

The goals of this Laboratory have been to simultaneously provide relevant neutron cross section measurements while studying the structure of nuclei. The extensive experimental measurements of neutron scattering from ^7Li followed by intensive analysis of these data have provided cross section data, new insights into the structure of ^8Li and a check on model calculations of other theorists. The study of the $^7\text{Li} + n$ system is a prime example of the realization of the goals of the Laboratory.

PRELIMINARY INPUT PARAMETERS

```

RUN 7LI L-S 15.5 7.0160 1.0067 0.1 0.1 8.0
-0.478 -4.633
4.3 4.3 4.3
0.5 1.5 0.5 3.5
JPI 0 + 1 1 1 1
CHAN      1 2 3
L      1 1 3
S      1 1 3
J      1.5 0.5 3.5
LEV1 2.3 0.7 0.0 0.0
      1 0.1
      2 0.0 0.1
      3 0.0 0.0 0.1
BC      -0.270 -0.3 -3.168
JPI 0 - 1 1 0 1
CHAN      1 2
L      2 0
S      2 0
J      1.5 0.5
LEV1 20. 0.0 0.0
      1 0.1
      2 0.0 0.1
BC      -1.068 0.0
JPI 1 + 3 2 2 1
CHAN      1 2 3 4 5 6 7
L      1 1 3 1 1 3 3
S      1 2 2 0 1 3 4
J      0.5 1.5 2.5 0.5 1.5 2.5 3.5
LEV1 0.7 0.6 1.1 0.0 0.6 0.6 0.0 0.0
      1 0.1
      2 0.0 0.1
      3 0.0 0.0 0.1
      4 0.0 0.0 0.0 0.1
      5 0.0 0.0 0.0 0.0 0.1
      6 0.0 0.0 0.0 0.0 0.0 0.1
      7 0.0 0.0 0.0 0.0 0.0 0.0 0.1
BC      -0.270 -0.270 -2.44 -0.3 -0.3 -3.168 -3.168
JPI 1 - 3 2 1 2
CHAN      1 2 3 4 5 6
L      0 2 2 0 2 2
S      1 1 2 1 1 3
J      0.5 1.5 2.5 0.5 1.5 2.5
LEV1 2.5 0.0 1.5 0.0 0.0 0.0 0.0
LEV2 5.0 0.4 0.0 0.0 -0.2 -0.2 1.0
      1 0.0
      2 0.0 0.1
      3 0.0 0.0 0.1
      4 0.0 0.0 0.0 0.1
      5 0.0 0.0 0.0 0.0 0.1

```

6	0.0	0.0	0.0	0.0	0.0	0.1						
BC	0.0	-1.068	-1.068	0.0	-1.165	-2.256						
JPI 2 + 4 2 3 1												
CHAN		1	2	3	4	5	6	7	8	9		
	L	1	1	3	3	1	3	1	3	3		
	S	1	2	1	2	1	1	3	3	4		
	J	0.5	1.5	2.5	3.5	1.5	2.5	1.5	2.5	3.5		
LEV1 8.0		2.4	0.0	0.0	0.0	1.0	0.0	-1.0	0.0	0.0		
	1	0.1										
	2	0.0	0.3									
	3	0.0	0.0	0.1								
	4	0.0	0.0	0.0	0.1							
	5	0.0	0.0	0.0	0.0	0.1						
	6	0.0	0.0	0.0	0.0	0.0	0.1					
	7	0.0	0.0	0.0	0.0	0.0	0.0	0.2				
	8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1			
	9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1		
BC	-0.270	-0.270	-2.344	-2.344	-0.3	-2.444	-1.455	-3.168	-3.168			
JPI 2 - 3 2 2 2												
CHAN		1	2	3	4	5	6	7				
	L	0	2	2	2	2	2	2				
	S	2	1	2	1	0	3	4				
	J	0.5	1.5	2.5	2.5	1.5	1.5	2.5				
LEV1 6.0		1.1	0.0	0.0	0.0	0.0	0.0	1.0				
LEV2 2.0		2.5	0.0	0.0	2.0	0.0	0.0	0.0				
	1	0.3										
	2	0.0	0.1									
	3	0.0	0.0	0.1								
	4	0.0	0.0	0.0	0.1							
	5	0.0	0.0	0.0	0.0	0.1						
	6	0.0	0.0	0.0	0.0	0.0	0.1					
	7	0.0	0.0	0.0	0.0	0.0	0.0	0.1				
BC	0.0	-1.068	-1.068	-1.165	-1.165	-2.256	-2.256					
JPI 3 + 3 2 4 1												
CHAN		1	2	3	4	5	6	7	8	9		
	L	1	3	3	3	3	1	1	3	3		
	S	2	1	2	0	1	3	4	3	4		
	J	1.5	2.5	3.5	2.5	3.5	0.5	1.5	2.5	3.5		
LEV1 0.12		0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
	1	0.2										
	2	0.0	0.1									
	3	0.0	0.0	0.1								
	4	0.0	0.0	0.0	0.1							
	5	0.0	0.0	0.0	0.0	0.1						
	6	0.0	0.0	0.0	0.0	0.0	0.1					
	7	0.0	0.0	0.0	0.0	0.0	0.0	0.2				
	8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1			
	9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1		
BC	-0.270	-2.344	-2.44	-2.444	-2.444	-1.455	-1.455	-3.168	-3.168			
JPI 3 - 2 1 3 1												
CHAN		1	2	3	4	5	6					
	L	2	2	2	0	2	2					
	S	1	2	1	3	3	4					

```

      J  1.5 2.5 2.5 0.5 1.5 2.5
LEV1 3.3 1.0 1.0 1.0 0.0 0.0 0.0
      1  0.1
      2  0.0 0.1
      3  0.0 0.0 0.1
      4  0.0 0.0 0.0 0.1
      5  0.0 0.0 0.0 0.0 0.1
      6  0.0 0.0 0.0 0.0 0.0 0.1
BC    -1.068 -1.068 -1.165 -0.935 -2.256 -2.256
JPI 4 + 2 1 4 1
      CHAN  1  2  3  4  5  6  7
      L    3  3  3  1  1  3  3
      S    1  2  1  3  4  3  4
      J    2.5 3.5 3.5 0.5 1.5 2.5 3.5
LEV1 10. 0.0 0.0 0.0 0.0 0.0 0.0 0.0
      1  0.1
      2  0.0 0.1
      3  0.0 0.0 0.1
      4  0.0 0.0 0.0 0.1
      5  0.0 0.0 0.0 0.0 0.1
      6  0.0 0.0 0.0 0.0 0.0 0.1
      7  0.0 0.0 0.0 0.0 0.0 0.0 0.1
BC    -2.344 -2.344 -2.444 -1.455 -1.455 -3.168 -3.168
JPI 4 - 1 0 3 1
      CHAN  1  2  3  4
      L    2  0  2  2
      S    2  4  3  4
      J    2.5 0.5 1.5 2.5
LEV1 4.0 1.1 0.0 0.0 0.0
      1  0.1
      2  0.0 0.1
      3  0.0 0.0 0.1
      4  0.0 0.0 0.0 0.1
BC    -1.068 -0.935 -2.256 -2.256
JPI 5 + 1 0 3 1
      CHAN  1  2  3  4
      L    3  1  3  3
      S    2  4  3  4
      J    3.5 1.5 2.5 3.5
LEV1 10. 0.0 0.0 0.0 0.0
      1  0.1
      2  0.0 0.1
      3  0.0 0.0 0.1
      4  0.0 0.0 0.0 0.1
BC    -2.344 -1.455 -3.168 -3.168
JPI 5 - 0 0 2 1
      CHAN  1  2
      L    2  2
      S    3  4
      J    1.5 2.5
LEV1 10.0 0.0 0.0
      1  0.1
      2  0.0 0.1

```

```

BC      -2.256  -2.256
JPI 6 + 0 0 2 1
CHAN    1      2
        L      3      3
        S      3      4
        J      2.5    3.5
LEV1    10.0    0.0    0.0
        1      0.1
        2      0.0    0.1
BC      -3.168  -3.168
JPI 6 - 0 0 1 1
CHAN    1
        L      2
        S      4
        J      2.5
LEV1    10.0    0.0
        1      0.1
BC      -2.256
JPI 7 + 0 0 1 1
CHAN    1
        L      3
        S      4
        J      3.5
LEV1    10.    0.0
        1      0.1
BC      -3.168
STOP

```

B. $^{11}\text{B}(n,n')^{11}\text{B}^*$ (2.12 MeV) Measurements. (P. Koehler et al.)

The program of the measurement of the inelastic differential scattering cross sections has actually moved ahead of schedule with the recent measurements of the 2.12 MeV group from $^{11}\text{B}(n,n')^{11}\text{B}$ at angles from 20° to 160° at incident neutron energies of 4.82, 5.00, 5.32, 5.46, 5.54, 5.62 and 6.00 MeV. According to the anticipated schedule listed in the report by F.G. Perey of the coordination meeting held at The Triangle Universities Nuclear Laboratory, Durham, North Carolina on March 5 and 6, 1979, these measurements were not expected until FY 80, however, we have been successful in obtaining distributions at several energies before the end of FY 79. These results are preliminary in that they are not yet corrected for multiple scattering, but the effect is not expected to be large. Shown in Figure 15 and 16 are angular distributions of the differential cross sections for the 2.12 MeV first excited state of ^{11}B at several energies of measurement. The cross sections are of the order of 10 - 20 mb/sr. The shape and magnitude change noticeably from one energy to another giving evidence of resonance structure in the compound nucleus ^{12}B . From the basic physics point of view it is hoped that with sufficient inelastic data over the resonances combined with our previous elastic data we will be able to determine more uniquely the energy level structure of ^{12}B . This, of course, requires setting up the R-matrix calculations to include both elastics and inelastics for ^{11}B neutron scattering. From the applied point of view, a good knowledge of the inelastic scattering cross section for ^{11}B is needed for proper shielding design for fusion reactors employing

Figure 15. Angular distributions of the differential inelastic cross section (arbitrary units) for the 2.12 MeV first excited state of ^{11}B at the incident neutron energies of 4.82, 5.00, 5.32 and 5.46 MeV. The lines through the data are Legendre polynomial fits.

Figure 16. Angular distributions of the differential inelastic cross section (arbitrary units) for the 2.12 MeV first excited state of ^{11}B at the incident neutron energies of 5.54, 5.62 and 6.00 MeV. The lines through the data are Legendre polynomial fits.

boron ($\sim 80\%$ ^{11}B) as a shielding constituent, Figure 17 shows on a plot of the total cross section the energies at which the inelastic measurements have been made by us, in this region of pronounced resonance structure. Assuming that the multiple scattering corrections for the inelastic cross sections are not too large, one can make a preliminary comparison of our data to data measured at other laboratories. At the lower energies measured the sum of the integrated elastic plus first inelastic (2.12 MeV level) cross sections, as measured by us, is approximately equal to the total cross section for neutrons on ^{11}B measured by Auchampaugh (AU 76). At the higher energies, the difference between the sum of 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 ($Q = -4.45, -5.02$ MeV) may contribute a considerable amount to the total cross section at these energies. Most of the differential inelastic cross section measurements from the 2.12 MeV level of ^{11}B made at other laboratories are outside the energy region of our present measurements (HO 69, PO 70). One comparison however can be made between our data and the previous measurements of Porter et al (PO 70) at an incident neutron energy of 4.82 MeV. The agreement in shape between the two sets of data is good, though there is only fair agreement in the absolute size of the two measurements. The difference between the two sets of measurements is perhaps to be expected since our data are not yet fully corrected for the effects of multiple scattering. Figure 18 shows the relative energy dependence of the Legendre polynomial coefficients for the expansion of our differential inelastic (2.12 MeV level) cross section measurements. Notice that there is resonance structure in all

Figure 17. Total cross section for neutrons on ^{11}B , together with the integrated elastic cross section. Arrows point to energies at which we have measured the differential inelastic cross section from the 2.12 MeV first excited state of ^{11}B .

Figure 18. Legendre expansion coefficients (arbitrary units) for the differential inelastic cross section from the 2.12 MeV level of ^{11}B .

five coefficients, although B_0 and B_2 contain the most. Comparison with Figure 17 shows that this initial survey is over rather widely spaced points in energy, and that substantially more points that are selectively chosen will be needed for proper resonance analysis. These results are preliminary at this point with the corrections for multiple scattering as the only major correction yet to be applied.

The only theoretical calculations of differential scattering cross sections for ^{11}B are those of Heil (HE 73) based upon the shell model in the continuum. It will be interesting to test the theory as our results unfold in the future.

C. R-Matrix Analysis of $^{11}\text{B}(n,n)^{11}\text{B}$ Data. (R. Lane et al.)

The final R-matrix analysis of all of our $^{11}\text{B}(n,n)^{11}\text{B}$ elastic differential scattering data from 0 to 8 MeV was delayed by a minor computer program difficulty together with the departure of Dr. Roger White, the Post Doctoral leading that effort, for a permanent position at Lawrence Livermore Laboratory. The checking of final R-matrix results after removal of the program bug is nearly finished. No substantive changes in the basic conclusions have been observed, although minor variations in some of the best-fit parameters may occur. The manuscript for the final journal publication is largely written, and is expected to be submitted for publication in the Fall. All data from these measurements have been sent to NNDC at BNL.

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

The study of elastic and inelastic scattering of neutrons from ^{13}C was motivated by several factors: i) the poor state of knowledge of energy levels of ^{14}C ; ii) the need to know differential data at energies of strong resonances in ^{13}C for correcting ^{12}C data so it can be better used as a standard; and iii) the opportunity to collaborate with Dr. George Auchampaugh of LASL in the purchase and use of the ^{13}C sample. The R-matrix analysis of the initial survey measurements of elastic scattering is nearly completed and is referred to in the next section. While our elastic data, which was the first differential scattering data ever reported for ^{13}C , revealed considerable new and interesting properties of the ^{14}C system, we have initiated a program of inelastic measurements to cross-check some assignments made by the elastic results and to learn more of the configurations in the wavefunctions for states of ^{14}C . Initial inelastic results for incident neutron energies 5.33 and 6.00 MeV obtained last winter were reported at the Washington Meeting of the APS, April, 1979. These results together with those from our most recent experiment last month (5.70, 6.25, and 6.49 MeV) are shown in Figures 19, 20, & 21. Figure 22 shows on a plot of total cross section the energies at which the inelastic measurements were made. Complete angular distributions (from 20° to 160° at 17.5° increments) were obtained for the first three inelastic groups at every energy except 5.33 where a complete distribution was possible for only the first inelastic group. The results are preliminary at this point. Corrections need to be made in three areas: i) none of the inelastic

Figure 19. Angular distributions of the differential inelastic cross section (arbitrary units) for the 3.09 MeV first excited state of ^{13}C at the incident neutron energies of 5.69, 6.00, 6.24, and 6.49 MeV. The lines through the data are Legendre polynomial fits.

Figure 20. Angular distributions of the differential inelastic cross section (arbitrary units) for the 3.68 MeV second excited state of ^{13}C at the incident neutron energies of 5.69, 6.00, 6.24, and 6.49 MeV. The lines through the data are Legendre polynomial fits.

Figure 21. Angular distributions of the differential inelastic cross section (arbitrary units) for the 3.85 MeV third excited state of ^{13}C at the incident neutron energies of 5.69, 6.00, 6.24, and 6.49 MeV. The lines through the data are Legendre polynomial fits.

Figure 22. Total cross section for neutrons on ^{13}C . Arrows on the right point to energies at which we have measured differential inelastic cross sections of ^{13}C .

measurements have been corrected for multiple scattering; ii) the second and third inelastic groups were not completely resolved, so a fitting procedure will be needed; and iii) a continuum of neutrons from the gas cell of the neutron source must be removed from under the TOF peaks.

The latter is especially bothersome for all three of the inelastic groups from ^{13}C because the cross sections are relatively very small and these "deep" inelastics have very low energies compared to the elastics. This puts them at energies where the low-energy continuum of neutrons, mostly from the (p,n) reaction on the usual molybdenum entrance window to the tritium gas cell, has a high yield. Since the large continuum at low energies scatter elastically from the ^{13}C into the same energy region as the main peak of the $\text{T}(p,n)^3\text{He}$ neutrons scatters inelastically (deep) the contamination from the continuum cannot be removed by any simple background measurement. Worse yet, that continuum contained considerable resonance structure. On our most recent inelastic measurements last month following suggestions from Profs. Brient, Finlay and Rapaport based on their recent tests we tried a tungsten window of the same thickness (5 μm) as the usual molybdenum window and obtained a substantial reduction in the continuum neutrons. Furthermore, the continuum had very little in resonance properties compared to that for molybdenum, which allows the use of an interpolated subtraction for the remaining continuum with greater confidence.

These are, as far as we can determine, the first inelastic differential scattering cross sections reported for ^{13}C . Their shapes and energy dependences change markedly. We expect to combine these with our elastic data to make a comprehensive R-matrix study of ^{14}C . It should

be pointed out that as in the case of ${}^7\text{Li}$, ${}^{11}\text{B}$, etc., along with our inelastic measurement also comes the elastic data, so we will continue to fill-in and cross-check our elastic library of data as we proceed.

E. R-Matrix Analysis of ${}^{13}\text{C}(n,n){}^{13}\text{C}$ Data. (R. White et al.)

With full multiple scattering corrections applied to the second set of elastic differential cross section measurements we now have a rather complete set of elastic data from 1.25 MeV to 6.5 MeV and will be adding to it as the inelastic program progresses. The preliminary R-matrix analysis of the first set of data described in our previous Progress Report and at the Washington Meeting of the APS, April, 1978, is expected to be upgraded to include all the elastic data and completed in the next few months.

F. Theoretical Considerations. (P. Hoffmann-Pinther and R.O. Lane)

The present neutron elastic scattering measurements lead to assignments of level energies, spins and parities in ^{14}C . There have been several model calculations by which to interpret structure of the nuclei in the $A = 10 - 15$ region, most of them emphasizing ^{14}N for the $A = 14$ nucleus. This emphasis has been due, in part, to the lack of data, until recently, on ^{14}C . In general, these calculations can be grouped under the headings of intermediate coupling and weak coupling models. The intermediate coupling approach for the normal parity states of $A = 14$ nuclei has been used in (AM 64, CO 65, CO 67, GO 68 VA 69). Non-normal parity states were considered in (HS 70, JA 71, HS 75). In all these calculations some form of effective matrix elements were used. Other intermediate coupling calculations for normal parity states (HAa 66, HAb 66) have been based on realistic interactions. Two nucleons outside an inert ^{12}C core were considered in (TR 63) for the nucleus ^{14}N . The MSDI has been used to calculate normal (SA 73) and non-normal (RI 78) parity states, respectively. In all these calculations the normal parity state are assumed to arise from various recouplings of the ten p nucleons while the non-normal states consider one nucleon in the sd-shell. The weak coupling approach has been taken in (MI 75) and in expanded configurations in (LI 72).

Recent calculations specifically for ^{14}C have been carried out by Darema-Rogers (DA 79), Fortune (FO 78), and Mordechai (MO 78). Darema-Rogers used the Oak Ridge code to interpret the non-normal parity states while Fortune used effective matrix elements for particles in the

sd-shell and an inert ^{12}C core to interpret the excited normal parity states seen in the $^{12}\text{C}(t,p)^{14}\text{C}$ reaction. Mordechai employed the formalism of Lie who used expanded configurations and an ^{16}O core.

In the present calculation we have used a unified intermediate coupling model to interpret the level spectrum of ^{14}C obtained from the $^{13}\text{C} + n$ reaction and other experiments in terms of simple configurations arising from neutrons in the $1p_{1/2}$, and ds orbitals yet accounting for more complicated configurations. The unified model is based on the assumption that a reasonable picture of ^{14}C is given having its low-lying states being formed by coupling the states of two neutrons to the ground and lowest excited states of an appropriate $A - 2$ core. In this scheme complicated configurations in the $1p$ shell are absorbed into the core states which are treated collectively. The Hamiltonian for the system is given by:

$$H = H_c + H_{sp} + n \sum_{n=1}^2 Q_c \cdot Q_n + v_{ij}$$

where H_c is the Hamiltonian for the core, H_{sp} that of the two neutrons. Q_c and Q_n are the mass quadrupole operators of the core and neutrons, respectively, and their product represents the particle-core interaction. The residual interaction v_{ij} is a δ -force. The wavefunction for ^{14}C is then given by:

$$|J_c JIM\rangle = \sum_{j_1 j_2} \sum_{J_c} \langle j_1 j_2 J J_c : II \rangle |[(j_1 j_2)J]_A J_c : IM\rangle$$

where $|[(j_1 j_2)J]_A J_c : IM\rangle$ is an eigenfunction of the Hamiltonian $H_c + H_{sp}$. The subscript A indicates antisymmetrization of the two-neutron wavefunction.

Antisymmetrization between the two neutrons and the core is ignored under the assumption that the core states contain only small components of the orbitals available to the last two nucleons. Although one cannot write down the wavefunction for the core, one has the advantage of knowing a great deal about the matrix elements of many operators between core states. These matrix elements can be obtained from experimental data, i.e., in zeroth order, we take the core states to be the lowest states of ^{12}C .

Because of the relatively pure ($\sim 70\%$) $p_{1/2}$ nature of the ground state of ^{13}C (SA 72, DA 79) the model allows for an interpretation of the non-normal parity states of ^{14}C in terms of $^{13}\text{C} + n$. Spectroscopic factors are obtained by a simple recoupling.

The results of the calculation for the spectrum of non-normal parity states and collected experimental data is shown in Figure 23, while the results for the normal parity spectrum is given in Figure 24. The results of Darema-Rogers and Lie for non-normal parity states are included in Figure 23 and Figure 24 includes the result of Lie for normal parity states. Different parameters were used for the spectrum of the two parities.

The unified model calculation reproduces, in general, the spectrum of ^{14}C although contribution from some configurations due to coupling with the $p_{3/2}$ nucleons are not considered explicitly. Model two particle mixture amplitudes are in qualitative agreement with those used in fitting the experimental spectrum for the non-normal parity states up to 10 MeV. Wavefunctions appropriate to the 1^- and first 2^- states seen in the ^{13}C reaction reflect the values of the reduced widths for these states.

Figure 23. Experimental and calculated non-normal parity states in ^{14}C . See text.

Figure 24. Experimental and calculated normal parity states in ^{14}C . See text.

For the normal parity states the limitation of including collectively configurations due to $p_{3/2}$ neutrons is more severe, with the 0^+ ground state and 1^+ state at 11 MeV the most affected. The calculated mixture amplitudes show a concentration in one configuration while the fittings, in general, show a distribution over several configurations.

The above described structure studies have treated all states in ^{14}C as bound states. However, the particle continuum in this nucleus begins just above 8 MeV excitation energy and therefore states above this energy should be treated as resonances rather than bound states. In addition one should be able to interpret other experimental data, such as phase shifts and cross sections which reflect the continuum nature of these states. Thus, the above treatment should be extended to the continuum. An effort is currently in progress to secure proper functioning of a continuum shell model R-matrix formalism fortran code (TA 70) which treats two neutrons outside an inert core and has a particle-hole option (for ^{11}B). The code includes the effects of shell model configurations in which neutrons are allowed in the unbound region. The method is applicable to elastic as well as inelastic scattering. The basic ideas of the method will then be extended to the more complicated system of ^{14}C using 2p-1h and core-coupled bound states for a ^{13}C target.

G. Improved Source Spectrum Using Tungsten Windows for Tritium Gas Target. (H. Knox et al.)

For the study of deep inelastic neutron scattering, the neutron source must be as free as possible from continuum neutrons. Tritium gas cells with molybdenum entrance windows have been used extensively at this laboratory to provide a relatively clean neutron source via the $T(p,n)^3\text{He}$ reaction. Earlier work (BR 79) at this Laboratory indicated that the use of tungsten foils in place of the molybdenum foils might decrease the neutron continuum produced in the window by about an order of magnitude.

Tungsten foils of 5 μm thickness were obtained from Microfoils, Inc. of Argonne, Illinois and recently tested. Initial tests were made to determine the integrity of these foils under high beam currents and gas pressures. Helium gas filled cells were found to perform well with pressures as high as 30 PSI and beam currents (pulsed) up to 8 μA for extended periods of time. Similar foils were subsequently used in a recent experiment where the inelastic cross sections for neutrons scattered from ^{11}B and ^{13}C were measured. Typical running conditions were 4 μA of pulsed proton beam with 22 PSI of tritium gas in the cell. Two cells were used during the experiment, one receiving a total of two coulombs of charge during its use. No leaks in the foils developed and there was no noticeable degradation of the foils during the experiment.

Figure 25 shows a comparison of a monitor detector spectrum (lower curve) using a gas cell with the tungsten entrance foil taken during this experiment and a similar monitor spectrum using a gas cell

Figure 25. Comparison of continuum neutron spectra from tritium gas cell for 6.1 MeV protons. Upper curve is for a cell with a molybdenum entrance foil and lower curve is from a cell with a tungsten foil.

with a molybdenum foil from an earlier experiment. The incident proton energies and tritium gas pressures were the same for both experiments. With the tungsten foil there is about a factor of five decrease in the number of continuum neutrons. The bias of the monitor detector was not the same during these two experiments -- it was about a factor of two lower during the run with the tungsten foil. Taking this into account an estimate of an order of magnitude total decrease in the neutron continuum with the tungsten foil is not unreasonable.

III. The (n,z) Reaction Program. (S.M. Grimes, R.W. Finlay and J. Rapaport)

A. The Triplet Quadrupole Spectrometer Installation and Testing

Assembly of the Ohio University large-aperture, magnetic quadrupole triplet spectrometer was completed in early spring of 1979. Figure 26 shows the instrument as it appeared at that time. Preliminary testing with a large-area alpha particle source demonstrated that the design values for magnetic field gradients, solid angle, and energy band pass were achieved in practice.

The original vacuum system which consisted entirely of two liquid-nitrogen-cooled sorption pumps is quick, clean and convenient for many applications but does not provide adequate ultimate vacuum when the system is used with a cooled Germanium detector. An ion pump has been installed directly below the detector which provides vacuum in the 10^{-7} Torr range and eliminates most of the liquid nitrogen consumption during long experiments.

Initial operation of the spectrometer in the vicinity of the intense neutron source demonstrated quite clearly the need for additional detector shadowing and shielding. Massive brass plugs (Figure 27) were designed so that their inside dimensions interfered as little as possible with the orbits of charged particles within the band pass and still reduced the neutron flux at the position of the detector by an order of magnitude.

Mass identification of the detected particles by charged-particle time-of-flight techniques has been successfully tested and the On Line Data Acquisition System has been programmed to perform the mass-energy-time

Figure 26. The Spectrometer. The target chamber is the vertical cylinder at the extreme right. The motor-driven target ladder is not shown. The vertical cylinder in the upper left, above the Vacisorb pumps, is the liquid nitrogen reservoir for the intrinsic Germanium detector. The charged-particle flight path from target to detector is 3.4 m. The massive (10,000 kg.) magnetic lenses were originally constructed for the Princeton-Penn accelerator. The pivot post (lower right) attaches to the floor close to the neutron source. The entire assembly can be moved by one person with the help of commercially available air pads which require no fixed track. The laboratory space remains available for other uses such as the neutron scattering program.

Figure 27. Front view of the spectrometer with the entrance cone removed. Neutrons are produced in the gas cell (right of center). Charged particles produced by neutrons incident on the target (center) enter the magnetic field through the elliptical opening in the thick brass plug. The center of the entrance aperture contains the shadow bar (50 cm of brass) which protects the detector from the direct neutrons.

analysis on line. It has also been observed that the more traditional method of mass analysis in charged-particle spectroscopy - an E- ΔE telescope - provides a significant reduction in background simply by virtue of the two-detector-coincidence requirement. Unfortunately, thin silicon ΔE counters are not available in the large sizes which are optimum for this spectrometer application. A thin-window gas proportional counter has been built - but not yet tested - which should provide a useful ΔE coincidence signal over a wide range of charged-particle energies. The design is similar to that of a counter which has recently been developed at Lawrence Livermore Laboratory.

B. Initial Studies of (n,z) Reaction Cross Sections

The new quadrupole spectrometer has been used to study the neutron-neutron final state interaction in the reaction $D(n,p)nn$ at $E_n = 9$ and 11 MeV. The recoil proton spectrum was obtained with a silicon telescope detector. The overall resolution was extraordinarily good - 140 keV - which is considerably better than is required for the experiments of interest to this program. The study of this reaction will be extended to higher energies in the near future, and the results of this study will be reported at the International Conference on Nuclear Cross Sections For Technology in October.

Elastic scattering of neutrons by deuterium will also be measured by observing the recoil deuterons with the spectrometer. This technique will compliment traditional neutron scattering experiments since the observation of recoil deuterons at small angle is equivalent to the measurement of scattered neutrons at inaccessibly large angle. Both of

these experiments (n-d scattering and break-up) are valuable preliminary steps in a planned study of neutron scattering and break-up of tritium.

The production of charged particles by neutrons incident on potential structural materials is one of the immediate goals of this project. Experience that has been gained during these preliminary studies, especially in the areas of detectors, electronics, source reaction characteristics and shielding, will be essential when these experiments are attempted. Present plans call for a first look at the $^{58}\text{Ni}(n,p)$ and (n,α) reactions before the end of the present fiscal year.

In summary, the spectrometer development is nearly complete and the experimental program is underway. It is worth noting that the development program, per se, has generated considerable interest in the physics community. Dr. S.M. Grimes, who has returned to Livermore after a very successful visit, presented invited lectures of this program at Brookhaven, Duke, Ohio State University, and the University of Kentucky as well as a contributed paper at the Washington APS meeting. Professor Finlay gave a short invited paper at the "Telluride" Conference on (p,n) Reactions and the Nucleon-Nucleon Force. Mr. J.T. Weber, who was largely responsible for the construction and testing of the spectrometer, presented a paper at the spring meeting of the Ohio Section of the APS in partial fulfillment of the thesis requirements for his B.S. degree in Engineering Physics from the Ohio University Honors Tutorial College.

IV. Scientific Publications, Papers Presented, Colloquia, Seminars, Theses

A. Inelastic Scattering from Light Nuclei

A paper entitled, "Differential Neutron Scattering of ^6Li and ^7Li for Neutrons of 4 to 7.5 MeV Energy" was published in Nuclear Science and Engineering, **69**, 223 (1979), H.D. Knox, R.M. White and R.O. Lane.

The following are abstracts of papers presented at meetings and conferences:

The Asilomar, California Meeting of the
American Physical Society
Division of Nuclear Physics
1-3 November 1978

Differential Cross Sections of 2.3 and 2.8 MeV Neutrons Scattered from ^6Li and ^7Li . H.D. KNOX, R.M. WHITE, D.A. RESLER, P.E. KOEHLER, and R.O. LANE, Ohio U.--Neutrons from the $T(p,n)^3\text{He}$ source reaction were scattered from highly enriched samples of ^6Li (99.30%) and ^7Li (99.99%). Differential elastic and inelastic (0.478 MeV level) cross sections for neutrons scattered from ^7Li and differential elastic cross sections for neutrons scattered from ^6Li have been measured for 2.3 and 2.8 MeV neutrons. Measurements were made at nine angles from 20° to 160° by time-of-flight methods with a 6.6 m flight path. These $^7\text{Li} + n$ inelastic measurements are the first to be reported in this energy region. The present results show the $^7\text{Li} + n$ inelastic cross section to be isotropic at these energies. Comparison of the present $^6\text{Li} + n$ elastic results with previously reported experiments will be made.

The Washington Meeting of the
American Physical Society
23-26 April 1979

Positive Parity States of ^{14}C in the Core-coupling Model. P. HOFFMANN-PINTHER and R.O. LANE, Ohio U.--The excited positive parity states of ^{14}C are calculated in a framework in which the state formed from the single particle states available to two neutrons is coupled to the lowest states of an even-even core. The interaction between the

neutrons and the core is of the form given by de-Shalit¹ and the residual interaction is $(V+V'\vec{\sigma}_1\cdot\vec{\sigma}_2)\delta$. The single particle energies and core data are taken, as far as possible, from ¹²⁻¹³C data. The results are compared to experimental data and other calculations.

¹A. de-Shalit, Phys. Rev. 122, 1530(1961)

The Washington Meeting of the
American Physical Society
23-26 April 1979

Differential Inelastic Neutron Scattering from ¹¹B and ¹³C.

P.E. KOEHLER, D.A. RESLER, H.D. KNOX, R.M. WHITE, and R.O. LANE, Ohio U.-- Neutrons produced by the T(p,n)³He reaction with the Ohio University Tandem Van de Graaff were scattered elastically and inelastically from enriched samples of ¹¹B (97%) and ¹³C (98%). Differential cross sections were measured at angles from 20° to 160° with an NE213 liquid scintillator employing PSD and TOF techniques with a 3.6 meter flight path. Angular distributions for ¹¹B were measured at energies of 5.46, 5.62, and 6.00 MeV where considerable resonance structure exists in ¹¹B. The 2.12 MeV distribution showed considerable changes in shape over the energy region measured. Distributions for ¹³C were obtained at 5.34 and 6.00 MeV in a region of a broad resonance in the total cross section. Inelastic groups for the 3.09, 3.68 and 3.85 MeV levels, together with the elastic group were obtained at 6.00 MeV, while the 3.09 MeV group and the elastic group were obtained at 5.34 MeV. No previous inelastic measurements on ¹³C have been reported. Analysis of the data and comparisons with other elastic results will be discussed.

The following abstract has been submitted to the Knoxville Meeting of the Division of Nuclear Physics of the American Physical Society, October 18-20, 1979:

An R-Matrix Analysis of the ⁷Li + n System. H. KNOX and R.O. LANE, Ohio U.--A multi-level, multi-channel R-matrix analysis of the ⁷Li + n system has been completed. This study includes the analysis of available elastic scattering data and inelastic scattering data to the first two excited states of ⁷Li for incident neutron energies up to 8 MeV. The

resulting spin and parity assignments for levels in the compound ^8Li nucleus are in excellent agreement with those from a microscopic multi-channel cluster model calculation by H. Stowe and E. Zahn¹. The latter study predicted 1^+ , 1^- , 2^- and 3^+ levels near 1 MeV excitation energy and 3^- and 4^- levels near the $^5\text{He} + t$ threshold. The present work confirms the presence of these levels. A discussion of these results and comparisons with the spin and parity assignments of others will be given.

¹H. Stowe and W. Zahn, Nucl. Phys. A289, 317 (1977).

The following abstract has been submitted to the International Conference on Nuclear Cross Sections for Technology, October 22-26, 1979:

R-Matrix Analysis of Neutron Elastic and Inelastic Scattering Data. H.D. KNOX, R.O. LANE, D.A. RESLER, and P.E. KOEHLER, Ohio U.--A multi-level, multi-channel R-Matrix analysis program has been developed for analyzing neutron elastic and inelastic scattering data. This program operates on an IBM 370/158 computer in conjunction with a Tektronix 4025/2631 graphics terminal, providing a visual display of both experimental data and calculated fits. The program allows the use of either j-j or channel coupling schemes and angular momentum values through $\ell = 3$ are included. The program is being used to analyze neutron scattering data for light nuclei relevant to the nuclear energy program. The operation of the program and the results of a $^7\text{Li} + n$ analysis will be discussed.

A colloquium entitled "Study of the Higher Excitation States of ^{12}B via the Scattering of Neutrons from ^{11}B " was presented at Oak Ridge National Laboratory by R.M. White in the Fall of 1978.

A thesis entitled "Differential Inelastic Scattering of Neutrons from ^{11}B " was presented to the Honors Tutorial College, Ohio University, by Paul E. Koehler in partial fulfillment of the requirements for graduation with the degree of Bachelor of Science in Physics, June, 1979.

B. (n,z) Reaction Program

The following is the introduction from an article to appear in the Proceedings of the Conference on (p,n) Reactions and the Nucleon-Nucleon Force, Telluride, Colorado, March 28-30, 1979 by Roger Finlay:

Recent appearance in the nuclear physics literature of high quality measurements of neutron-induced charged-particle reactions has helped to rekindle interest in this largely-ignored branch of nuclear reaction studies. Other contributors to this conference describe results obtained with the techniques developed at the University of California at Davis. This contribution will focus on our efforts to develop and extend an alternative technique--using magnetic quadrupole lenses--which was pioneered at the Lawrence Livermore Laboratory. Since the Livermore methods have been previously described, comparison of the design features of the Ohio University spectrometer with the Livermore system should provide an efficient approach to the subject.

The first and most significant difference is that the Livermore spectrometer has been in service collecting data for nearly four years. The Ohio spectrometer was first assembled early in 1979 and has not yet passed the acid test of successful use in nuclear reaction studies. Nonetheless, enough progress has been achieved on the design and testing of the new instrument that a discussion at this time of its major features should be informative for many readers.

The following are abstracts of papers presented:

The Washington Meeting of the
American Physical Society
23-26 April 1979

A Large-Solid-Angle Quadrupole Spectrometer. S.M. GRIMES⁺, R.W. FINLAY, V. KULKARNI, J. RAPAPORT and J. WEBER, Ohio U.--A magnetic quadrupole triplet spectrometer has been designed and constructed for use in studying neutron-induced charged-particle-producing reactions. It is similar in concept to the spectrometer¹ in use at Lawrence Livermore Laboratory for similar measurements but has a much larger solid angle (10 msr).

Particle time-of-flight is used for mass identification. A spectrometer with this solid angle can be used with microampere pulsed beams, instead of the milliamper beam in use at Lawrence Livermore Laboratory.

[†]Permanent address: Lawrence Livermore Laboratory

¹K.R. Alvar et al., Nucl. Instrum. and Methods 148, 303 (1978).

The Ohio Section Meeting of the
American Physical Society
11-12 May, 1979

A Large-Solid-Angle Quadrupole Spectrometer. J.T. WEBER, S.M. GRIMES[†], R.W. FINLAY, V. KULKARNI, and J. RAPAPORT, Ohio U.--A triplet magnetic quadrupole spectrometer has been designed and constructed for use in studying neutron-induced charged-particle-producing reactions. This spectrometer is similar in design theory to a spectrometer¹ in use at Lawrence Livermore Laboratory, but has a much larger solid angle (~ 10 msr). Preliminary results will be presented.

[†]Permanent address: Lawrence Livermore Laboratory

¹K.R. Alvar et al., Nucl. Instrum. and Methods 148, 303 (1978).

The following abstracts have been submitted to the Knoxville Meeting of the International Conference on Nuclear Cross Sections For Technology, 22-26 October, 1979.

A study of Source Neutron Reactions. P. GRABMAYR, J. RAPAPORT, S.M. GRIMES[†], R.W. FINLAY and V. KULKARNI, Ohio U.--The $T(d,n)^4\text{He}$ and the $D(d,n)^3\text{He}$ reactions are widely used as source of monoenergetic neutrons at low deuteron energy. For energies higher than ~ 4 MeV contaminations of the monoenergetic neutron spectra are observed due to the breakup of the deuteron. Other contaminations origin from the entrance window of the gascell and the beamstop. In many experiments it is possible to discriminate against the breakup neutrons using a high energy bias. A different approach was undertaken at the Ohio University Tandem Accelerator Laboratory. The breakup of the deuteron on helium yield similar neutron energy spectra as the breakup on deuterium at the same bombarding energy. This was checked at several energies. The effect of different window materials on the continuous neutron spectrum was investigated and the results will be shown.

[†]Present address: Lawrence Livermore Laboratory

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 U.--A magnetic quadrupole triplet spectrometer has been constructed in order to study neutron-induced charged particle producing reactions. It is similar in concept to the spectrometer¹ in use at Lawrence Livermore Laboratory for similar measurements but has a much larger solid angle (~ 10 msr) and can be used with incident neutron energies up to 26 MeV. The reactions ${}^2\text{H}(n,p){}^2\text{n}$ and ${}^2\text{H}(n,d){}^2\text{n}$ have been studied at neutron energies up to 25 MeV using pulsed neutron beam produced by the Ohio University Tandem Van de Graaff Accelerator. Time-of-flight was used for particle identification. Preliminary experimental results and an outline of theoretical analysis will be presented.

[†]Permanent address: Lawrence Livermore Laboratory

¹K.R. Alvar et al., Nucl. Instrum. and Methods 148, 303 (1978).

V. Scientific Staff

Faculty Associate Collaborators:

Steven Grimes, Visiting Professor from Livermore
Roger Rinlay, Professor of Physics
Jacob Rapaport, Professor of Physics

Scientific Collaborating Visitor:

Dr. George Auchampaugh, Los Alamos Scientific Laboratory

Post Doctorates:

Harold Knox
Roger White (Terminated December 20, 1978)
Gerhard Randers-Pehrson (Began May 1, 1979)
Peter Hoffmann-Pinther (Theory Consultant, 5 months)

Graduate Students:

Paul Koehler (Began June 1979, previously undergraduate)
David Resler (Began June 1979, previously undergraduate)
Steven Graham, Summer 1979
Steven Mellema, Summer 1979
Paul Papenhausen, Summer 1979

Undergraduate Student:

John O'Donnell

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