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STUDY OF STRUCTURE OF LIGHT NUCLEI
WITH NEUTRONS

Progress Report

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ABSTRACT

The series of measurements of neutron elastic differential cross sections for ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^{10}\text{B}$ and ${}^{11}\text{B}$ for $4 \text{ MeV} \leq E_n \leq 8 \text{ MeV}$ is nearing completion with final results either published or submitted for publication. New elastic measurements for ${}^{13}\text{C} + n$ ($1.57 \text{ MeV} \leq E_n \leq 6.5 \text{ MeV}$) have been completed and these results are being studied with the R-matrix analysis program ORMAP. New elastic measurements for ${}^{11}\text{B} + n$ for $2 \text{ MeV} \leq E_n \leq 4 \text{ MeV}$ have also been completed and these new results along with the earlier measurements from $4 \text{ MeV} \leq E_n \leq 8 \text{ MeV}$ are being used in a comprehensive analysis of ${}^{11}\text{B} + n$ from 0 to 8 MeV. This analysis should be completed by early fall. Inelastic measurements on these same light nuclei have begun with differential cross sections for ${}^7\text{Li} + n$ (0.478 MeV level) completed at 2.3 and 2.8 MeV. Work on the assembly of the Ohio University quadrupole triplet spectrometer is progressing rapidly with the first experiments scheduled for this fall.

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INTRODUCTION

During the period since the previous report we have completed much of the work proposed for this year. This was done despite the fact that work had to be delayed by three months caused by the necessity to build a new tritium gas-handling system and furnace, and by well over another month by the shut-down of the Accelerator Laboratory at the University caused by severe power cut-backs necessitated by the prolonged coal miners' strike in our area. Despite these handicaps we have maintained good productivity of data for the Department of Energy. Our results have appeared in journals and laboratory reports, and have been sent to the National Nuclear Data Center at Brookhaven National Laboratory. During the past few weeks we have been working on solving a vacuum leak in the accelerator before proceeding on with further inelastic scattering measurements. Work is being begun on the (n, z) magnetic quadrupole spectrometer. Magnets and power supplies obtained as excess property are being checked out for faults, needed repairs, etc. Steel support material and air pads for moving the spectrometer have arrived and design is underway.

II. Differential Scattering Cross Section Measurements and Analyses

A. ${}^6\text{Li}$ and ${}^7\text{Li}$ Elastic Differential Scattering Cross Sections, for Neutrons of 4 to 7.5 MeV Energy

Our final results including numerical data in this area have been published as an Ohio University Report COO-2490-8, June 1978, and a condensation of the work has been submitted to Nuclear Science and Engineering for publication. We give here an abbreviated version of these final results.

The present results for ${}^6\text{Li}$ and ${}^7\text{Li}$ are shown in Figures 1 and 2 in the form of Legendre polynomial expansion coefficients for the differential scattering cross section. In both figures energies are given in the laboratory system. The coefficients for ${}^6\text{Li}$ are slowly varying with energy indicating very little resonance structure. Two broad resonances are seen in the ${}^7\text{Li}(n, n_0 + n_1)$ channel, probably caused by levels at excitation energies of $E_x = 6.1$ and 7.1 MeV in the ${}^8\text{Li}$ system.

Comparisons of the present results with those of Hopkins et al.¹⁾ are shown in Figure 3 for ${}^6\text{Li}$ and Figure 4 for ${}^7\text{Li}$. In these figures and all figures to follow, error bars are not shown if they are smaller than the symbols. For comparison with the present ${}^7\text{Li} + n$ measurements the differential elastic and inelastic cross sections of Hopkins et al.¹⁾ have been summed. In both figures the solid curves are least squares Legendre polynomial fits to the present data. The agreement between the two experiments is excellent at all energies.

Comparisons of the present results with those of Batchelor and Towle²⁾ are shown in Figure 5 for ${}^6\text{Li}$ and in Figure 6 for ${}^7\text{Li}$. Fully corrected values of the actual experimental data points of Reference 2 are not available. Instead, they present tabulated differential cross sections at an arbitrary

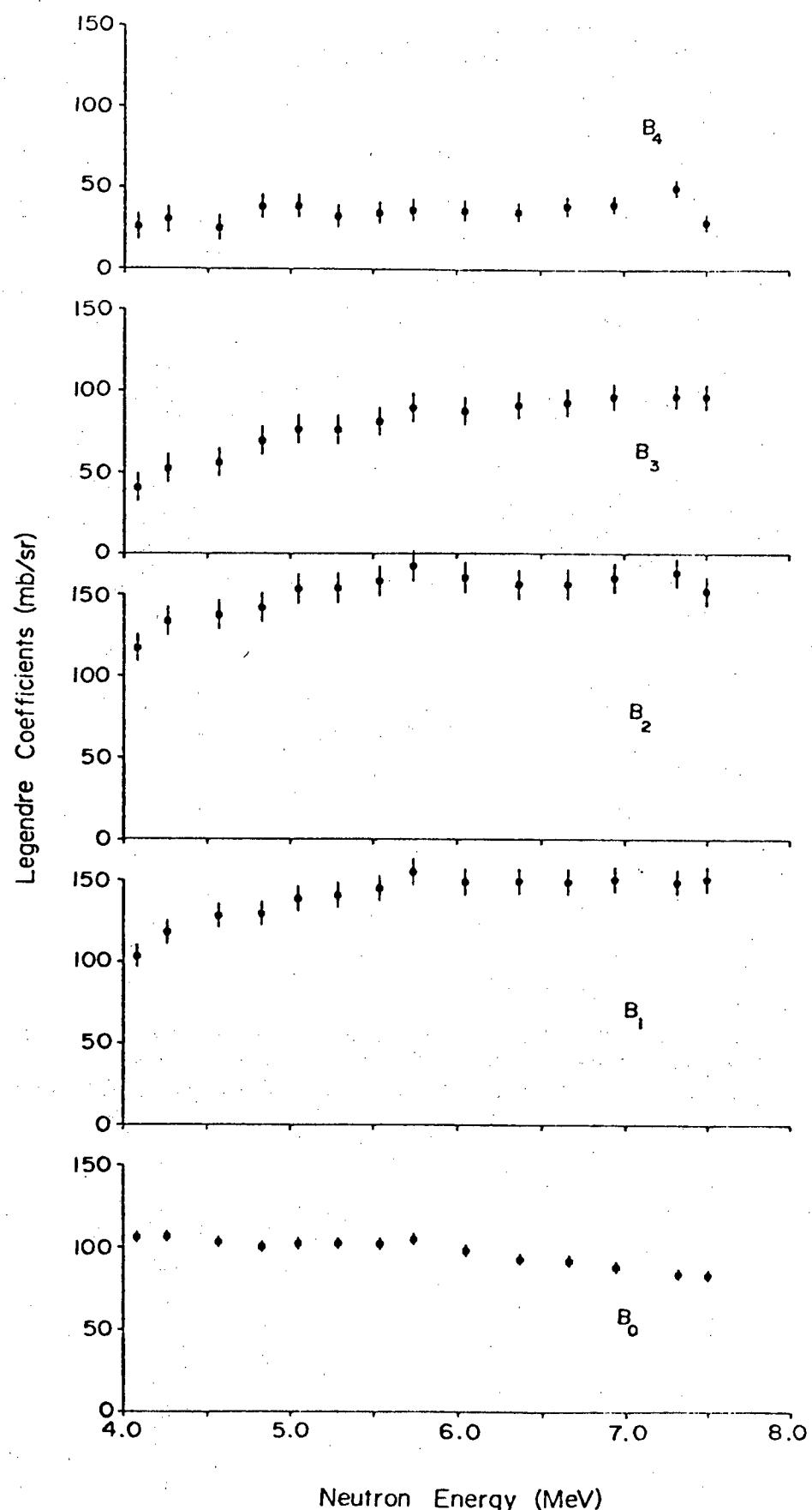


Figure 1. Legendre polynomial expansion coefficients of the present ${}^6\text{Li} + \text{n}$ data versus neutron energy. The coefficients represent center-of-mass cross sections while neutron energies are in the laboratory system.

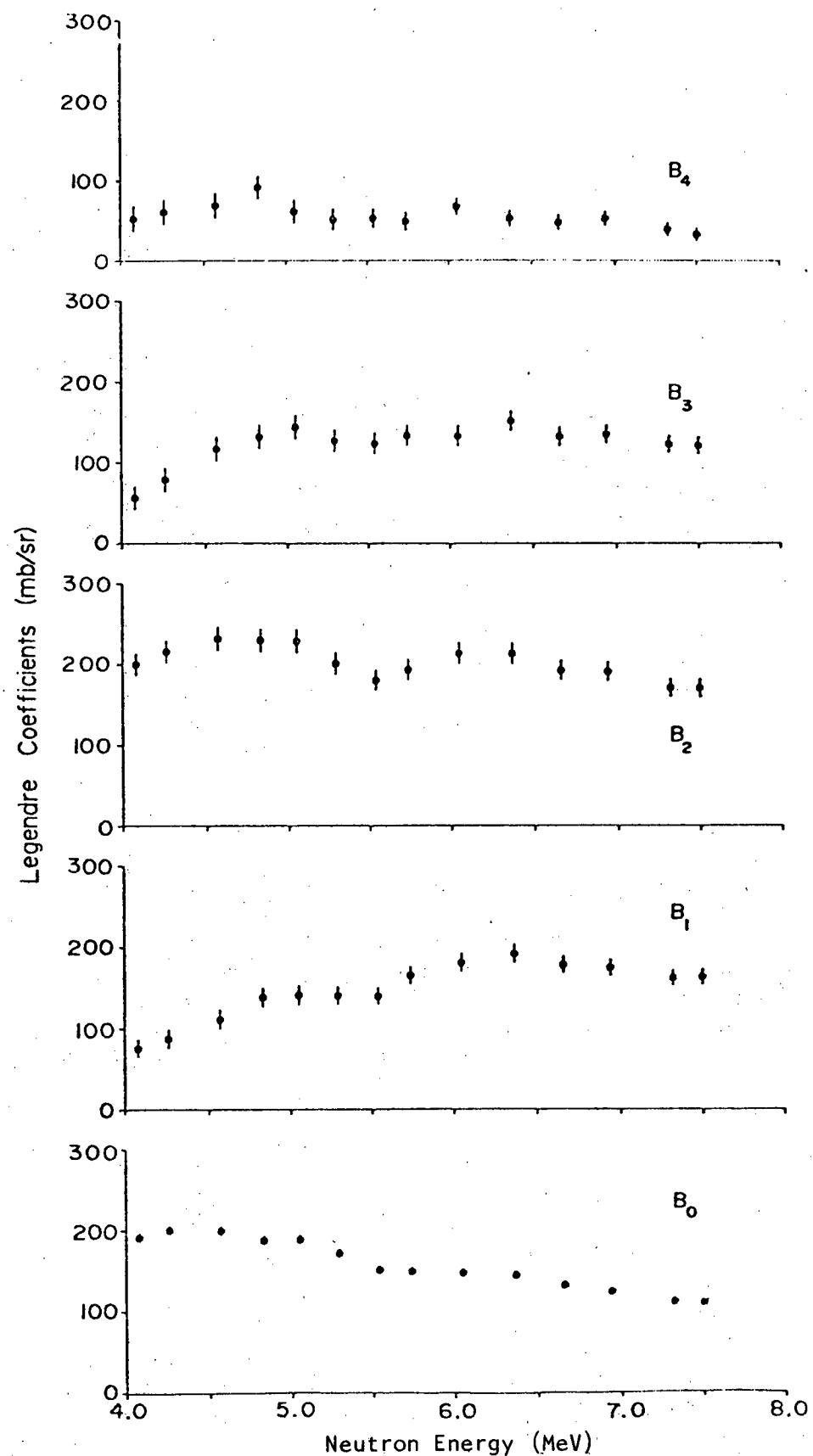


Figure 2. Legendre polynomial expansion coefficients of the present ${}^7\text{Li}(n, n_0+n_1)$ data versus incident neutron energy. The coefficients represent center-of mass cross sections while neutron energies are in the laboratory system.

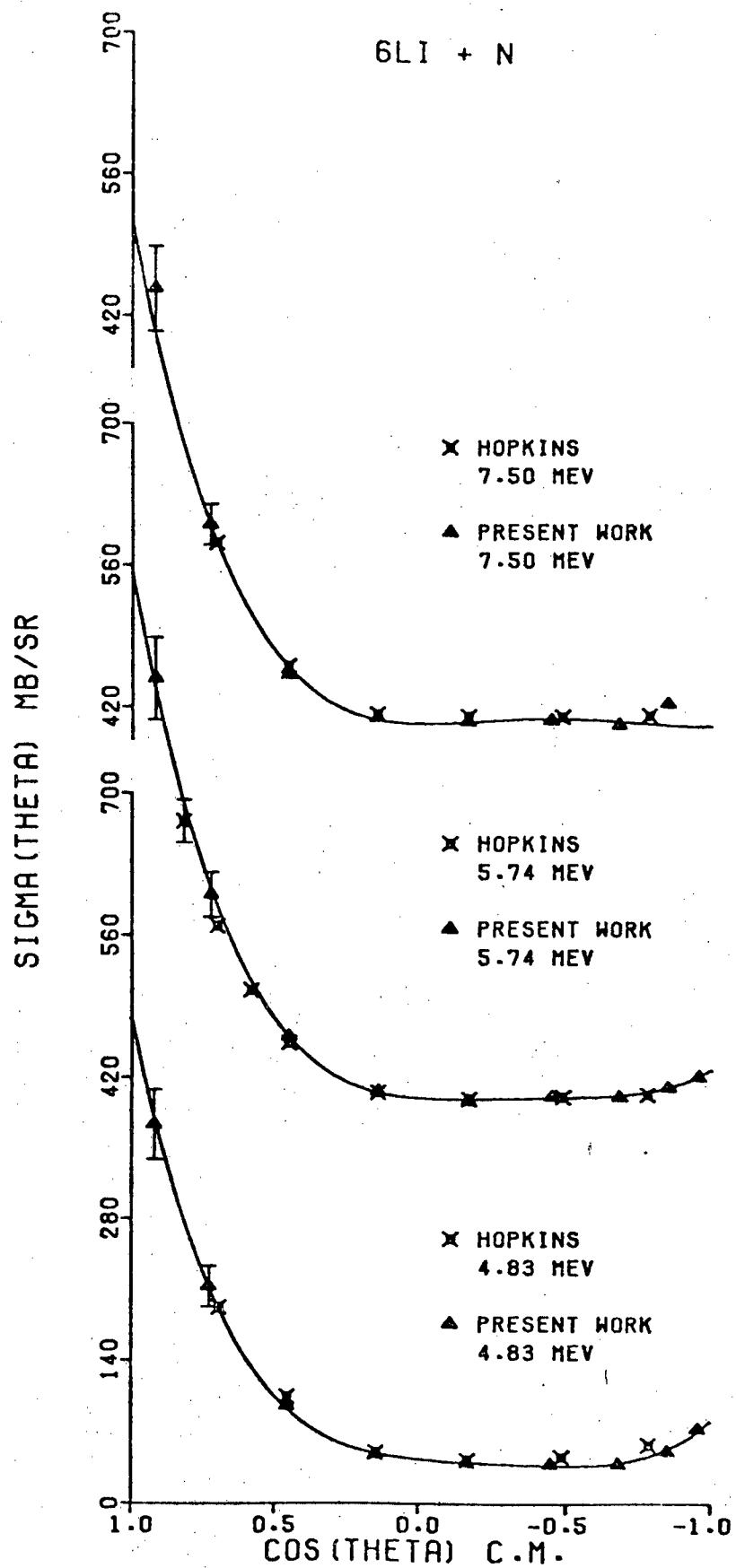


Figure 3. Comparisons of the present ${}^6\text{Li} + \text{n}$ data with the measurements of Hopkins *et al.* (Reference 1). The solid curve is a least squares Legendre polynomial fit to the present data.

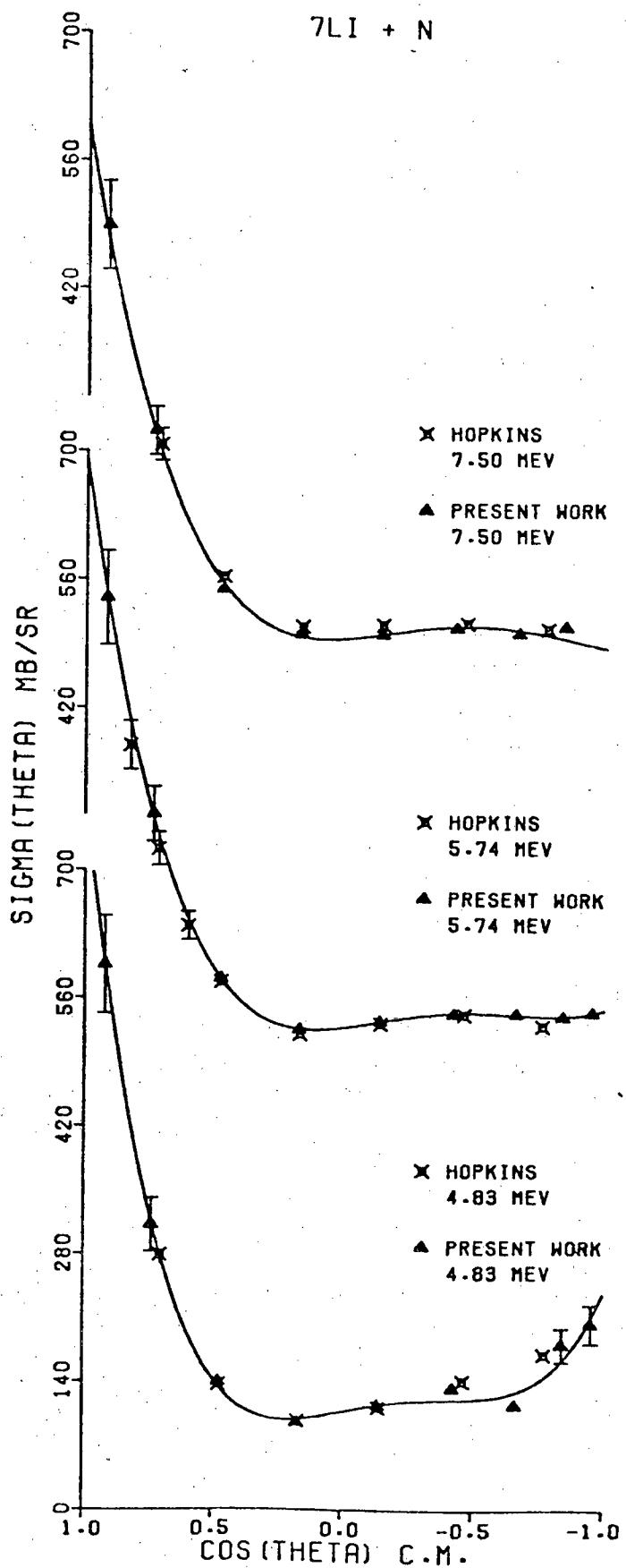


Figure 4. Comparisons of the present $^{7}\text{Li}(n, n_0 + n_1)$ data with the measurements of Hopkins *et al.* (Reference 1). The solid curve is a least squares Legendre polynomial fit to the present data.

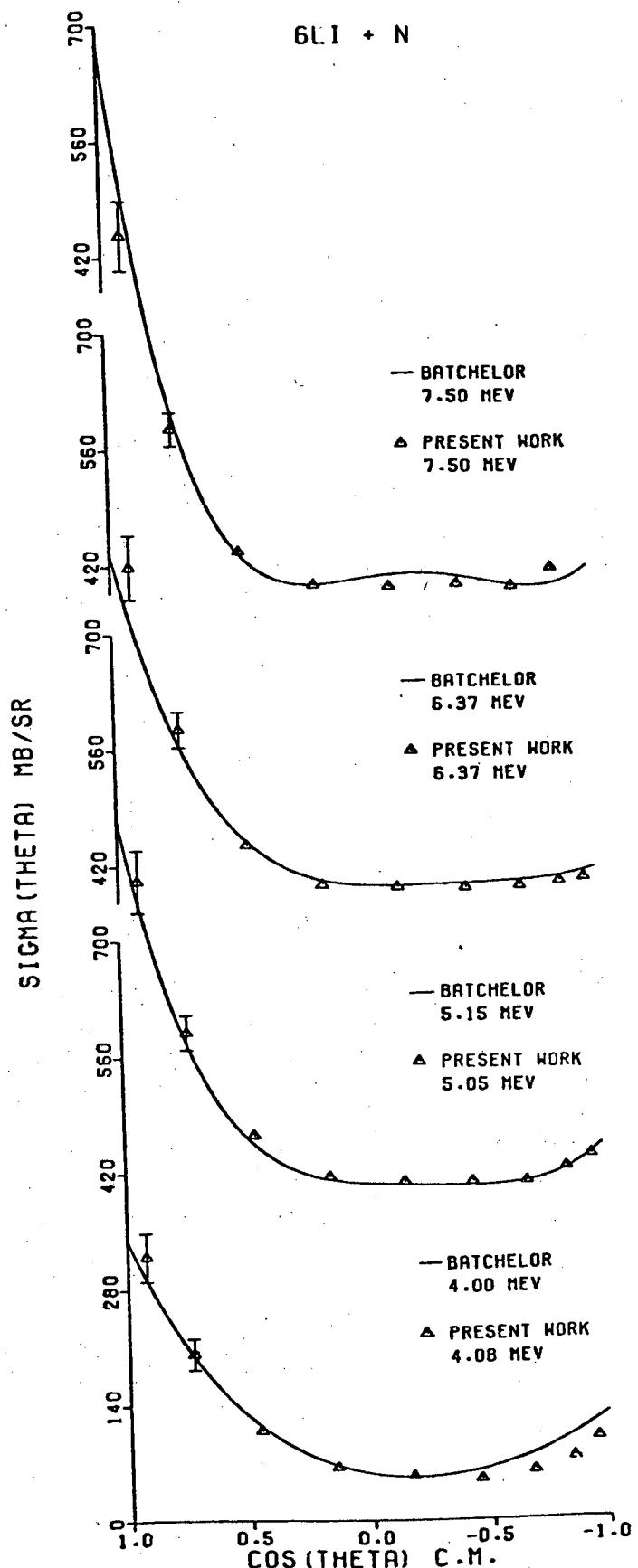


Figure 5. Comparisons of the present ${}^6\text{Li} + \text{n}$ data with the evaluated results of Batchelor and Towle (Reference 2). The solid curves are least squares Legendre polynomial fits to the numerical cross sections obtained by Batchelor and Towle after corrections were made to their experimental data.

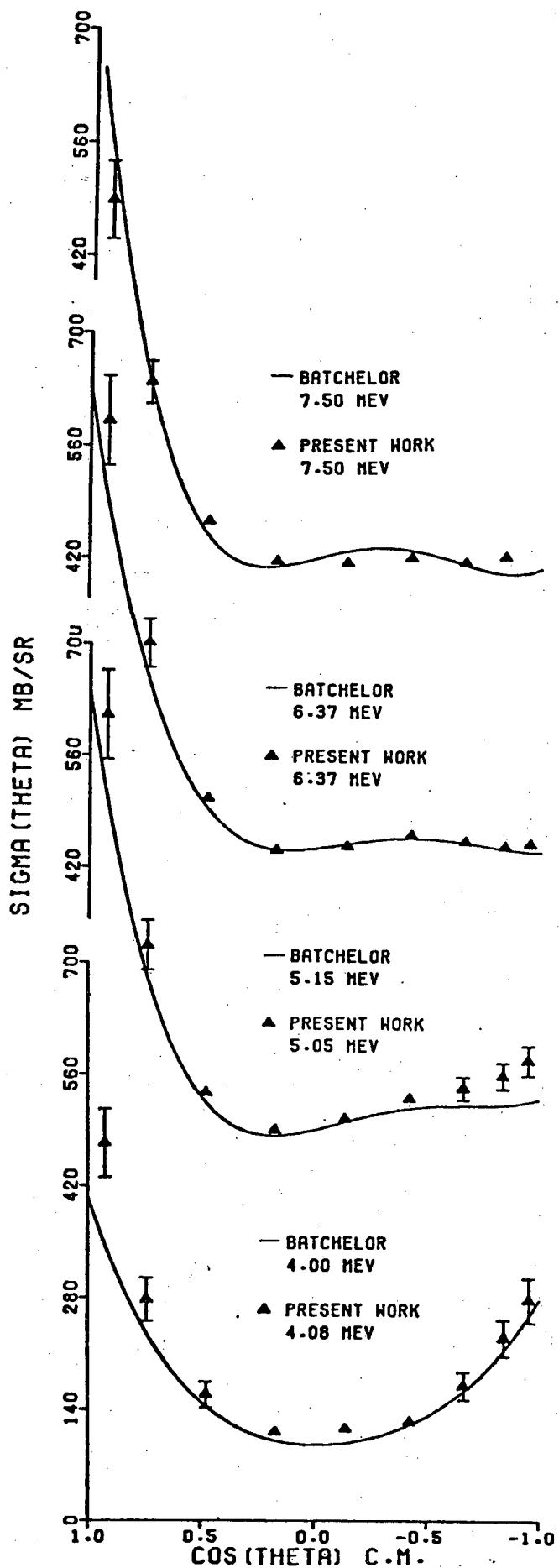


Figure 6. Comparisons of the present ${}^7\text{Li}(n, n_0+n_1)$ data with the evaluated results of Batchelor and Towle (Reference 2). The solid curves are least squares Legendre polynomial fits to the numerical cross sections obtained by adding the inelastic cross sections of Batchelor and Towle to their tabulated elastic cross sections.

set of angles which were based on a fitted curve which, in turn, had been corrected for multiple scattering and finite geometry. In Figure 5 the solid curve is a least squares fit of the tabulated data of Reference 2 for ${}^6\text{Li}$. The agreement between this curve and the present experimental data is generally good. For ${}^7\text{Li}$, Batchelor and Towle²⁾ obtained values for the elastic cross section by subtracting estimates of the differential inelastic cross sections from their corrected distributions. For purposes of comparison with the present ${}^7\text{Li}$ results, these estimates were added back again to the tabulated elastic results of Reference 2 to give the ${}^7\text{Li}(n, n_0+n_1)$ differential cross sections. The solid curves in Figure 6 are least squares fits to the results for ${}^7\text{Li}(n, n_0+n_1)$ derived from Reference 2 in this manner. Except at 7.5 MeV, the present data tend to be higher than the results of Batchelor and Towle²⁾ particularly at forward angles.

Comparison of the present ${}^6\text{Li}$ differential cross sections with the current ENDF/B-IV evaluations are shown in Figure 7 and the integrated ${}^6\text{Li}$ cross sections are shown in Figure 8. The agreement for both differential and integrated cross sections with ENDF/B-IV is excellent. Similar comparisons for ${}^7\text{Li}$ are shown in Figures 9 and 10 respectively. Except at the highest energy the evaluated differential cross sections tend to be lower than the present data particularly at the forward angles and this is reflected in the integrated values.

Differential cross sections for 1.5 to 4 MeV neutrons scattered from ${}^6\text{Li}$ have been recently measured by A.B. Smith⁶⁾ at Argonne National Laboratory. Two measurements were made by Smith⁶⁾ at 4.00 MeV. These results are shown in Figure 11 along with the present data at 4.08 MeV. The solid curve is a least squares Legendre polynomial fit to the present data. The two measurements by Smith⁶⁾, labeled "Data Set 1" and "Data Set 2" in Figure 11, were made

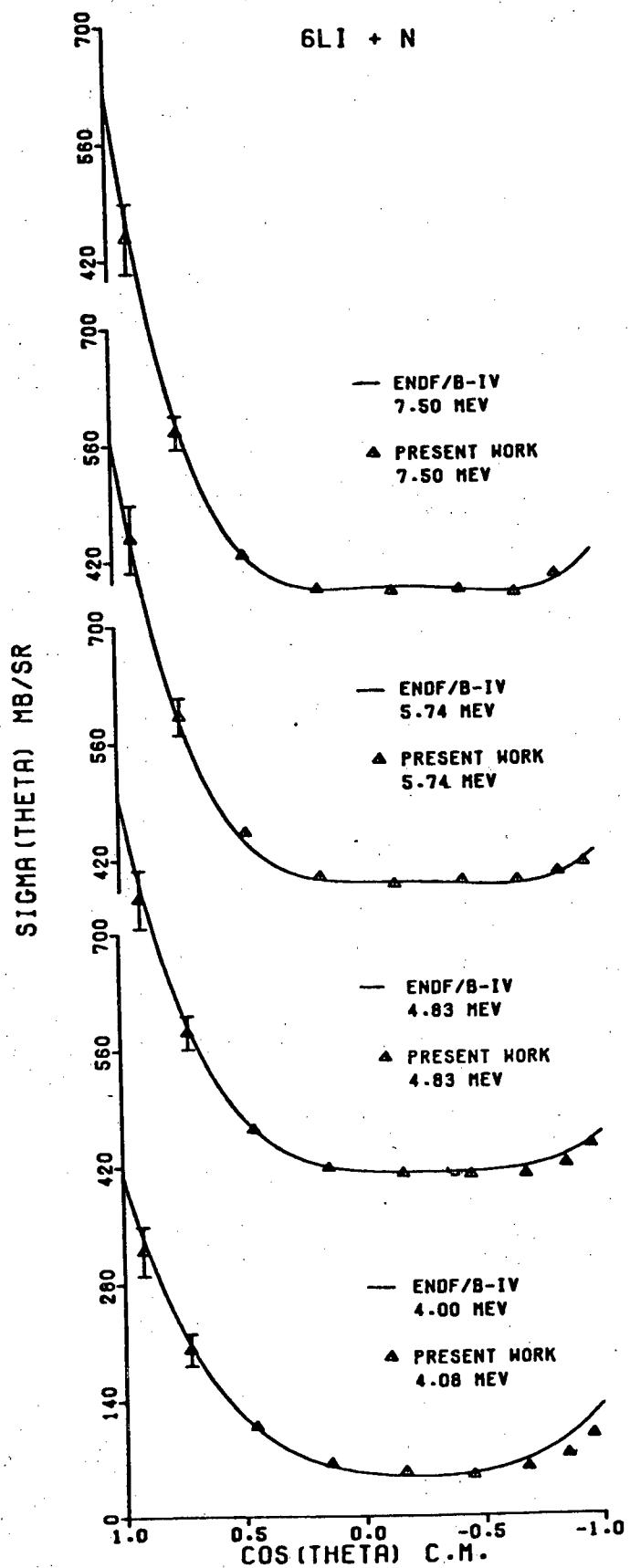


Figure 7. Comparisons of the present ${}^6\text{Li} + \text{n}$ differential data with the ENDF/B-IV evaluation.

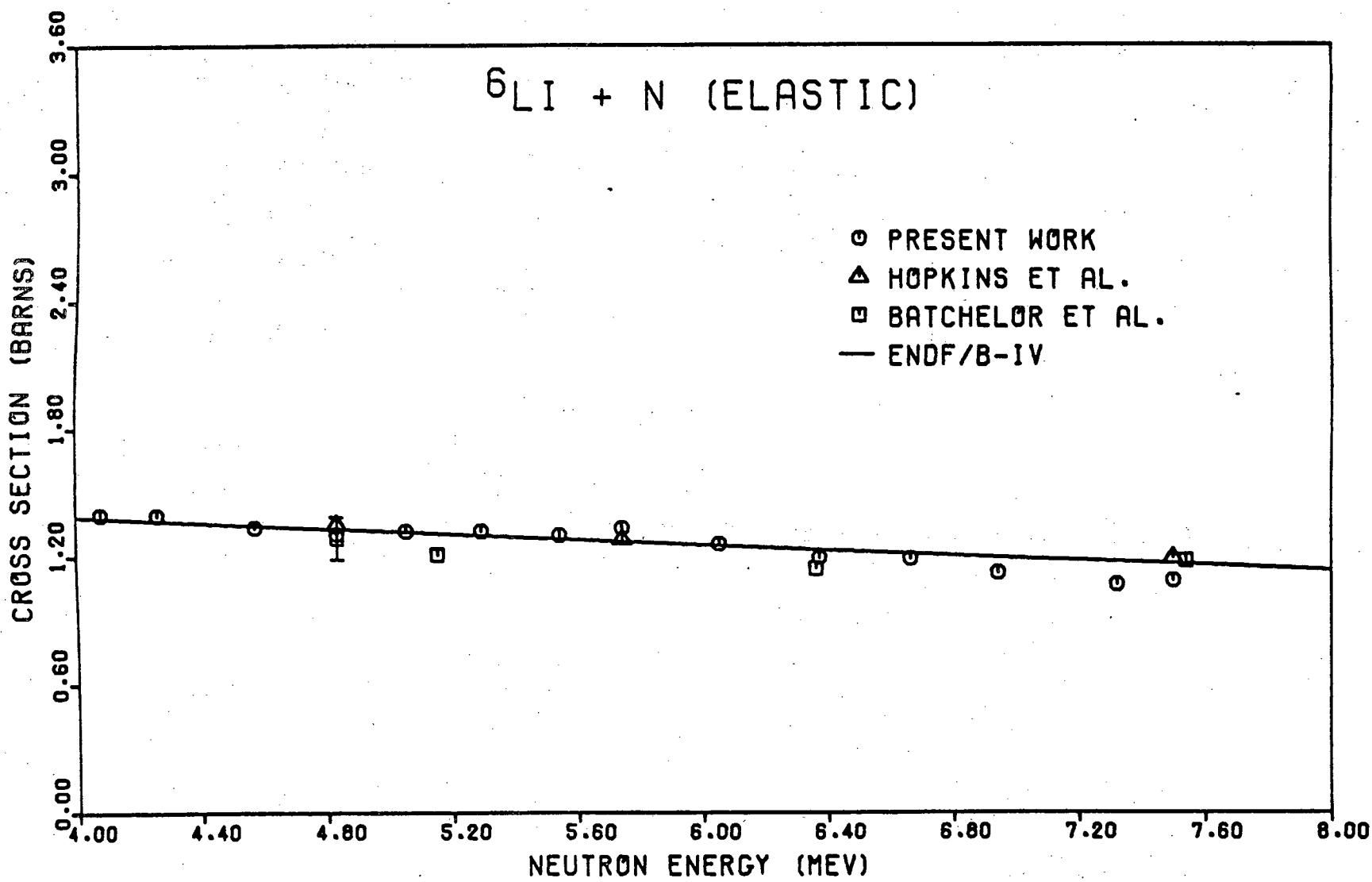


Figure 8. Comparison of the integrated elastic cross sections for ${}^6\text{Li} + \text{n}$ of the present work, Hopkins et al., (Reference 1) Batchelor and Towle (Reference 2) and the ENDF/B-IV evaluation.

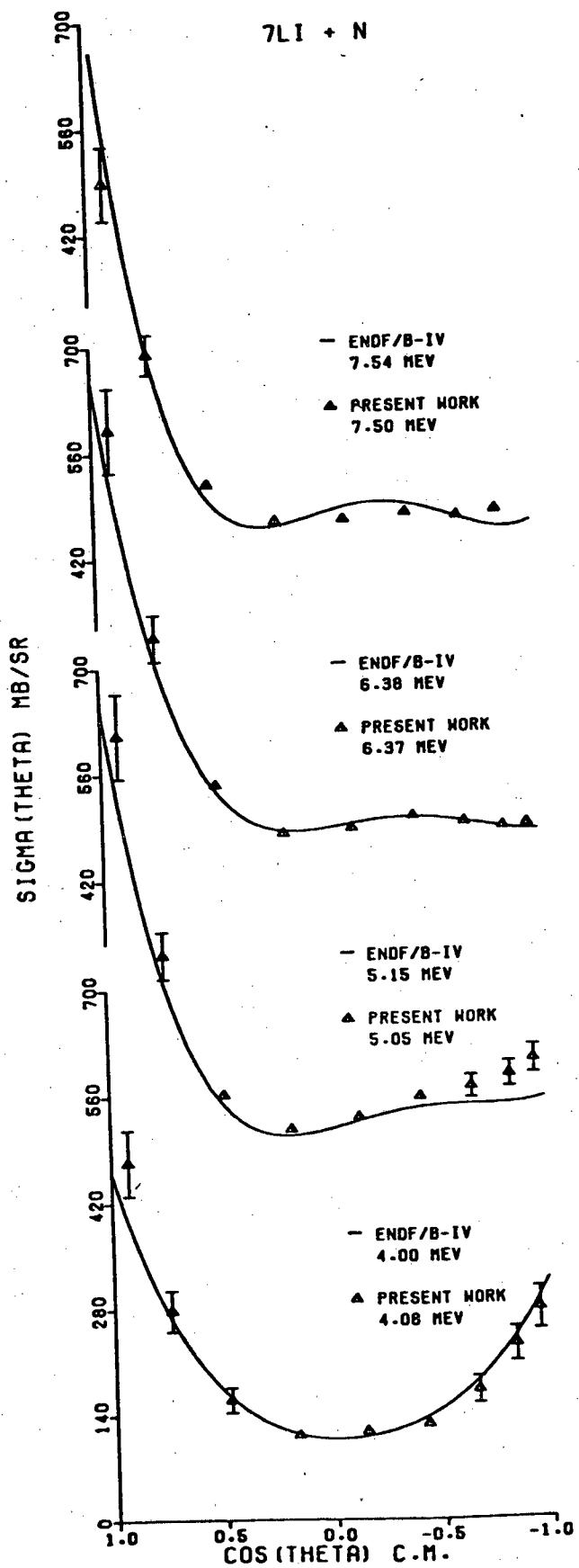


Figure 9. Comparisons of the present ${}^7\text{Li}(n, n_0+n_1)$ differential data with the ENDF/B-IV evaluation.

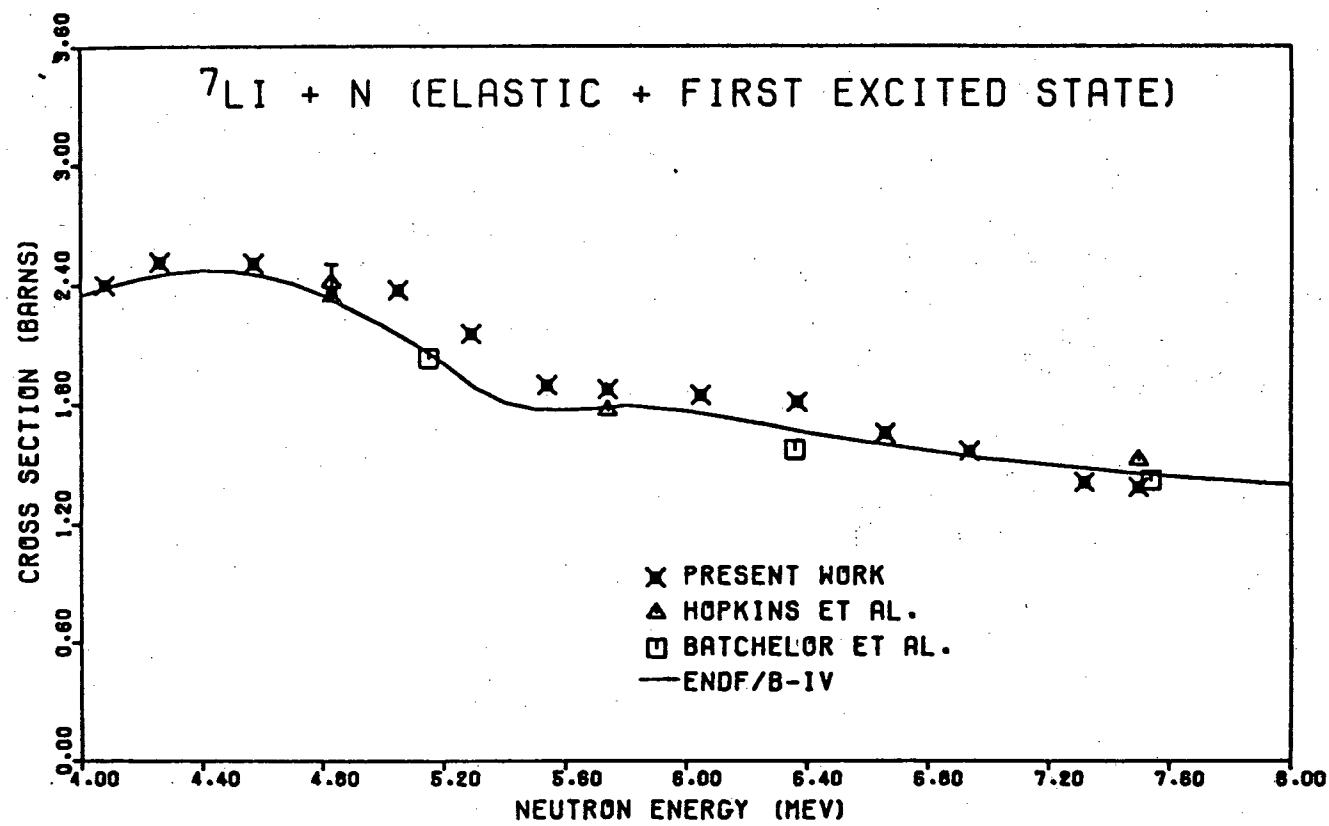


Figure 10. Comparison of the integrated ${}^7\text{Li}(n, n_0+n_1)$ cross sections of the present work, Hopkins *et al.* (Reference 1), Batchelor and Towle (Reference 2) and the ENDF/B-IV evaluation.

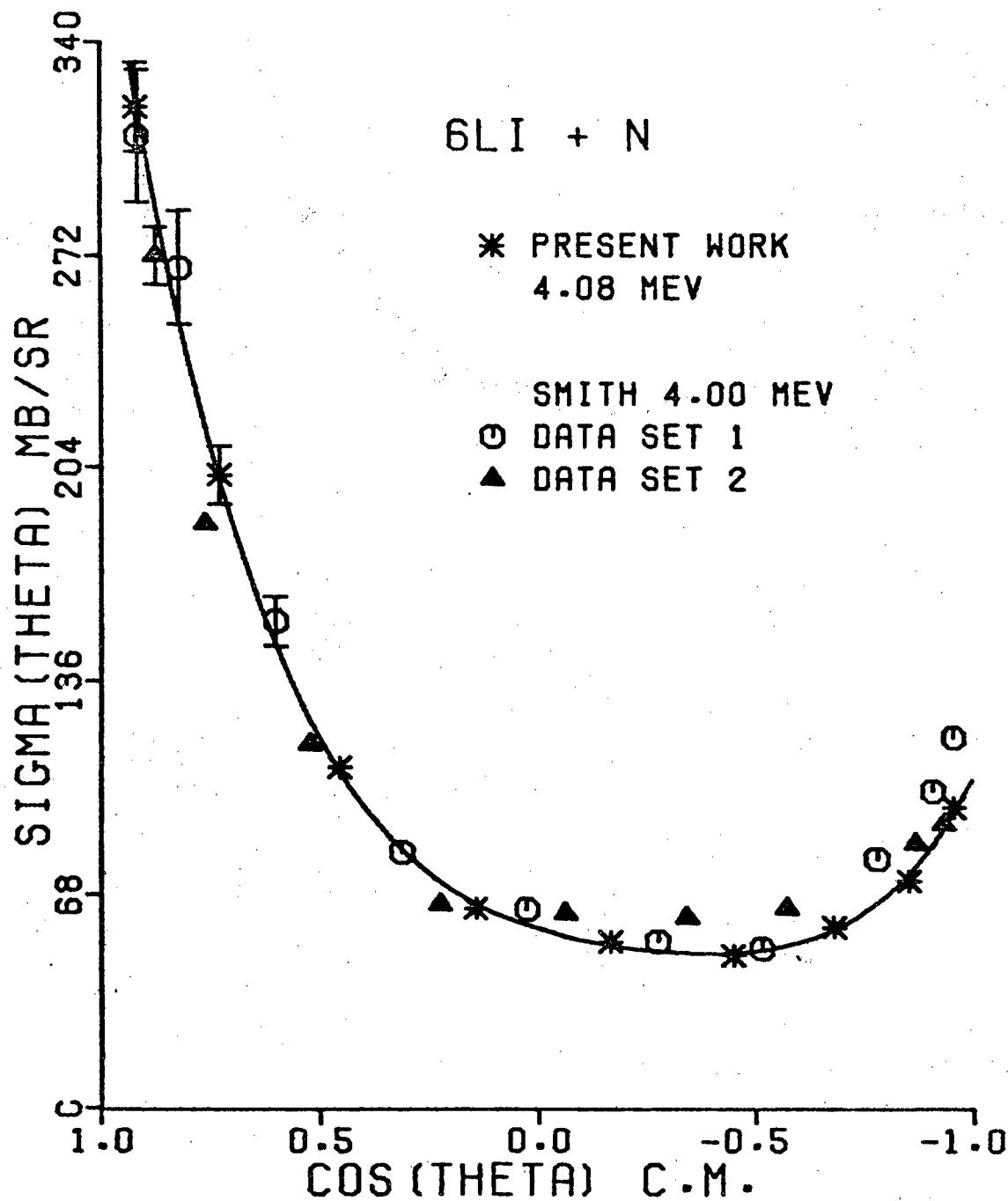


Figure 11. Comparison of the present ${}^6\text{Li} + \text{n}$ experimental results with those of A. Smith (Reference 6). The solid curve is a least squares polynomial fit to the present data.

using scattering samples of different size. The errors associated with Data Set 1, made with a very small scattering sample, are approximately twice those of Data Set 2. At forward angles, the present data and those of Smith⁶⁾ agree very well, while those of Smith⁶⁾ are slightly higher at backward angles.

Differential cross sections for neutrons scattered from both ^6Li and ^7Li have been measured at Duke University by F.O. Purser⁷⁾ for $7.0 \leq E_n \leq 15$ MeV. A comparison of the present results with the Duke results is shown in Figure 12. The agreement is excellent.

The results from Argonne⁶⁾, Duke University⁷⁾, the present work, and the earlier work by Lane et al.⁸⁾ provide differential cross sections for the lithium isotopes up to 15 MeV. In each of these experiments sufficient energy overlap was allowed for comparisons with the data of other experiments. With the excellent comparisons seen here, the combined results provide consistent and detailed measurements throughout the range of energies where data is needed for fusion energy applications.

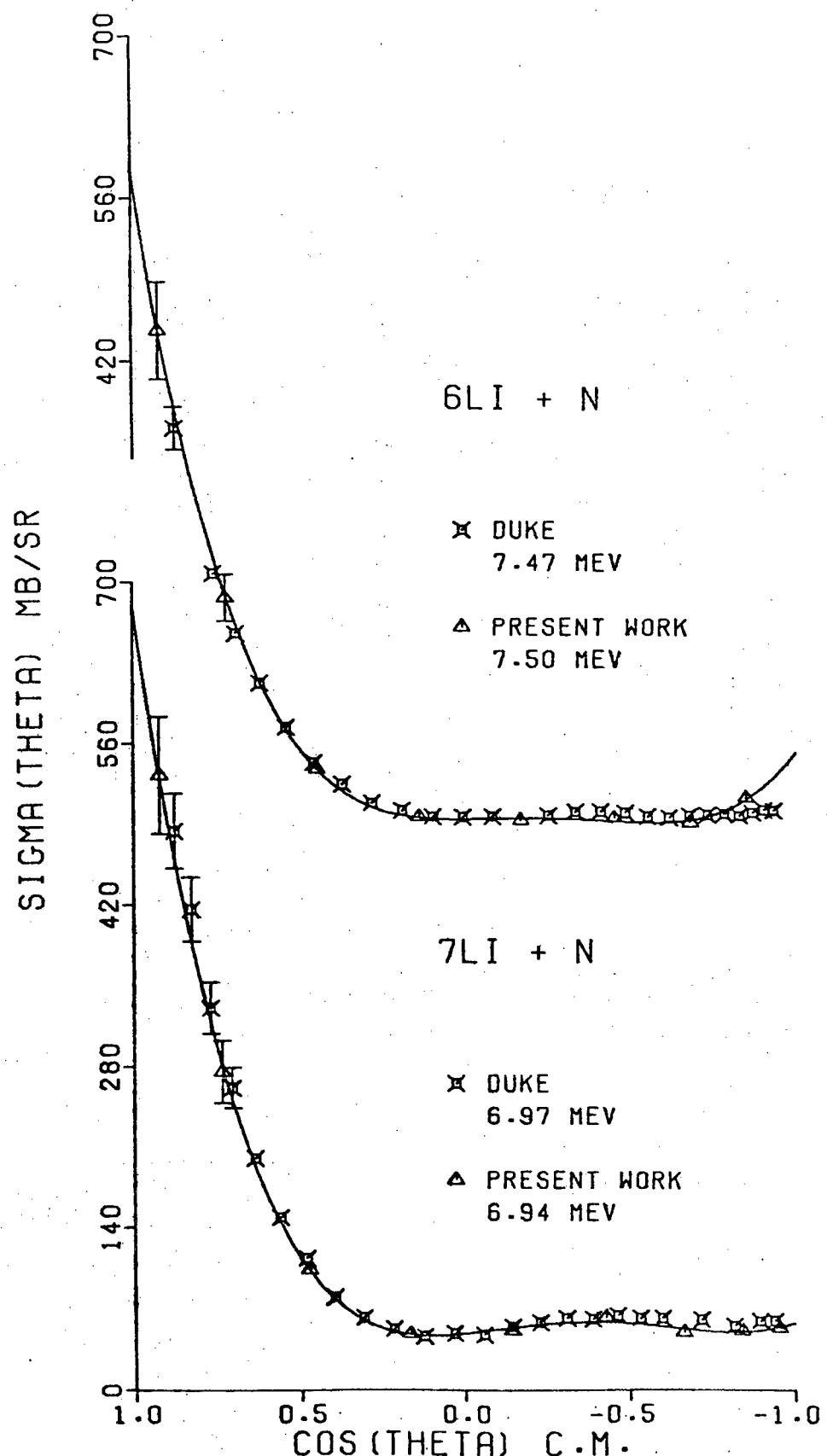


Figure 12. Comparison of the present results with the Duke results (Reference 7). The solid curve is a least squares Legendre polynomial fit to the present data.

B. ^7Li Inelastic Scattering, 4 - 7.5 MeV

The ^7Li results shown in Section A above included the 0.478 MeV inelastic scattering from ^6Li and ^7Li using new highly enriched samples and longer flight paths designed to obtain more accurate inelastic data.

Although complete separation of the 0.478 MeV inelastic group from the elastic group for $^7\text{Li} + n$ was not possible, the inelastic cross sections were obtained by curve-fitting methods. These inelastic data are summarized in Figure 13. Shown here are three typical differential inelastic cross sections throughout the energy range studied. Generally the cross sections tend to be nearly isotropic at the lower energies and are characterized by increasingly more negative B_2 Legendre expansion coefficients as the incident energy increases. Shape-wise this is in agreement with the work of Hopkins et al.¹⁾ at 4.08 MeV. The present inelastic data yield higher integrated cross sections than those of Dickens et al.⁹⁾ near 4 MeV but agree with these authors from about 5 to 7.5 MeV.

Described below is a new series of measurements on inelastic scattering from ^6Li and ^7Li using new highly enriched samples and longer flight paths designed to obtain more accurate inelastic data.

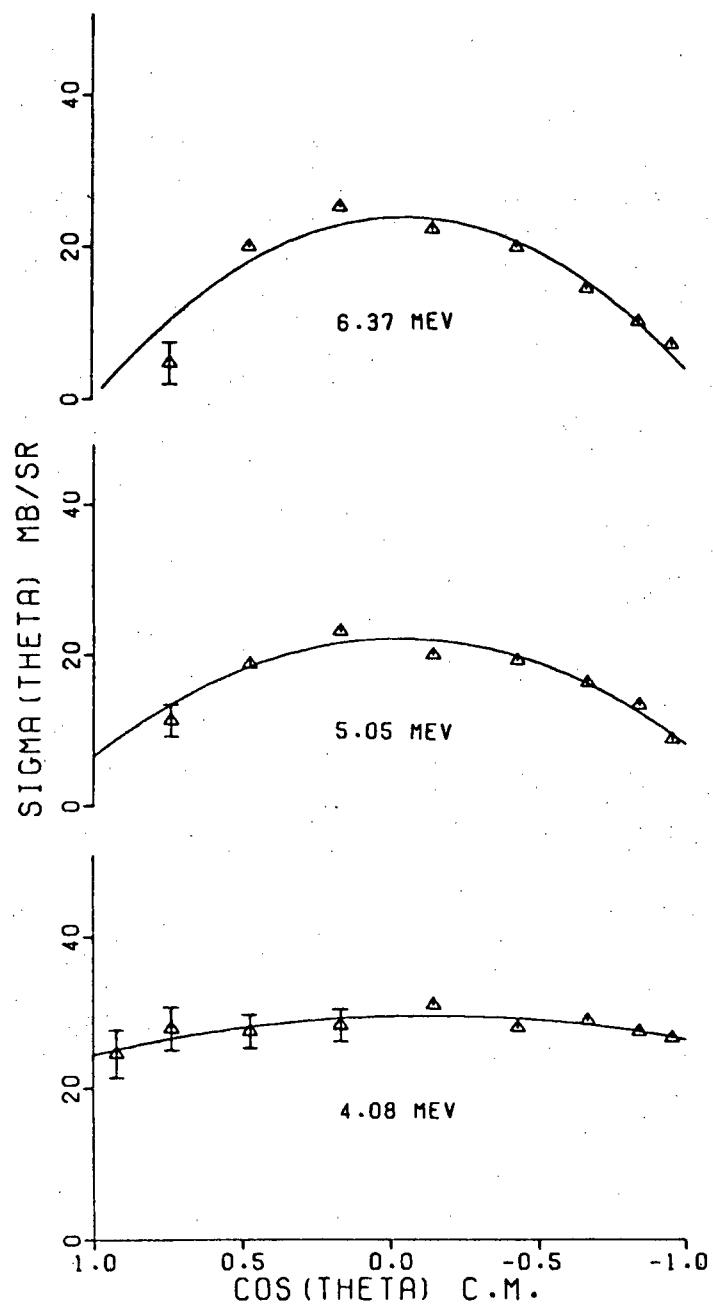


Figure 13. Typical differential inelastic (0.478 MeV level) cross sections for ${}^7\text{Li} + \text{n}$ in the 4 to 7.5 MeV incident neutron energy region.

C. ^7Li Elastic and Inelastic Scattering, ^6Li Elastic Scattering 2-3 MeV

A series of new measurements of the differential elastic and inelastic (0.478 MeV level) neutron cross sections for ^7Li has begun. Measurements at 2.3 MeV and 2.8 MeV have been completed and at least three more distributions up to 4.5 MeV will be completed in the next month. These measurements are being made with a 6.5 m flight path in order to resolve the elastic and inelastic groups. In addition to the 7000 1b detector shield used in our previous elastic measurements a large water tank weighing approximately 4500 lbs is being used to provide additional neutron shielding for these difficult and lengthy measurements.

A typical subtracted time-of-flight spectrum for these $^7\text{Li} + n$ measurements is shown in Figure 14. This spectrum is for 2.3 MeV neutrons scattered from ^7Li at an angle of 107.5° . The two groups are very well resolved in this energy region. Preliminary analysis of these inelastic data show the cross section to be isotropic in the center-of-mass system. The integrated inelastic cross section agrees well with previous $^7\text{Li}(n, n'\gamma)^7\text{Li}$ work.

Along with these elastic and inelastic cross sections for ^7Li the elastic differential cross sections for neutrons scattered from ^6Li are being measured. At the lower incident energies, the $^6\text{Li} + n$ data provide a check of the entire system since comparisons of these values with those of Knitter *et al.*¹⁰⁾ can be made. These comparisons are shown in Figure 15 for 2.3 MeV and Figure 16 for 2.8 MeV. The agreement is very good. For higher energy measurements, where the separation between the elastic and inelastic group decreases, some fitting of the data may be necessary to extract both the elastic and inelastic cross sections for ^7Li . At these energies the $^6\text{Li} + n$ data will also provide line shape information necessary for this fitting procedure.

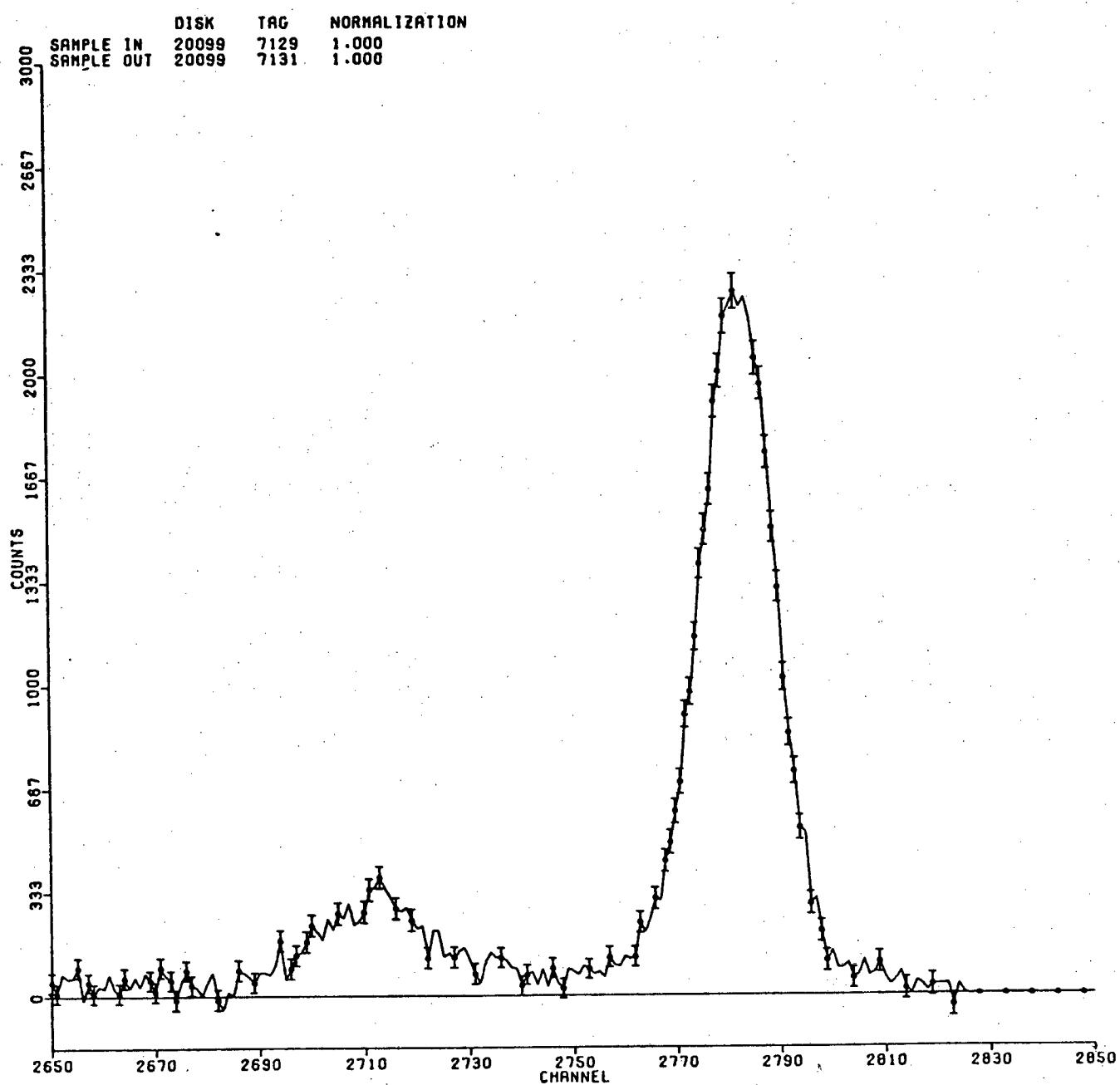


Figure 14. A typical subtracted time-of-flight spectrum for the ${}^7\text{Li} + \text{n}$ inelastic measurements.

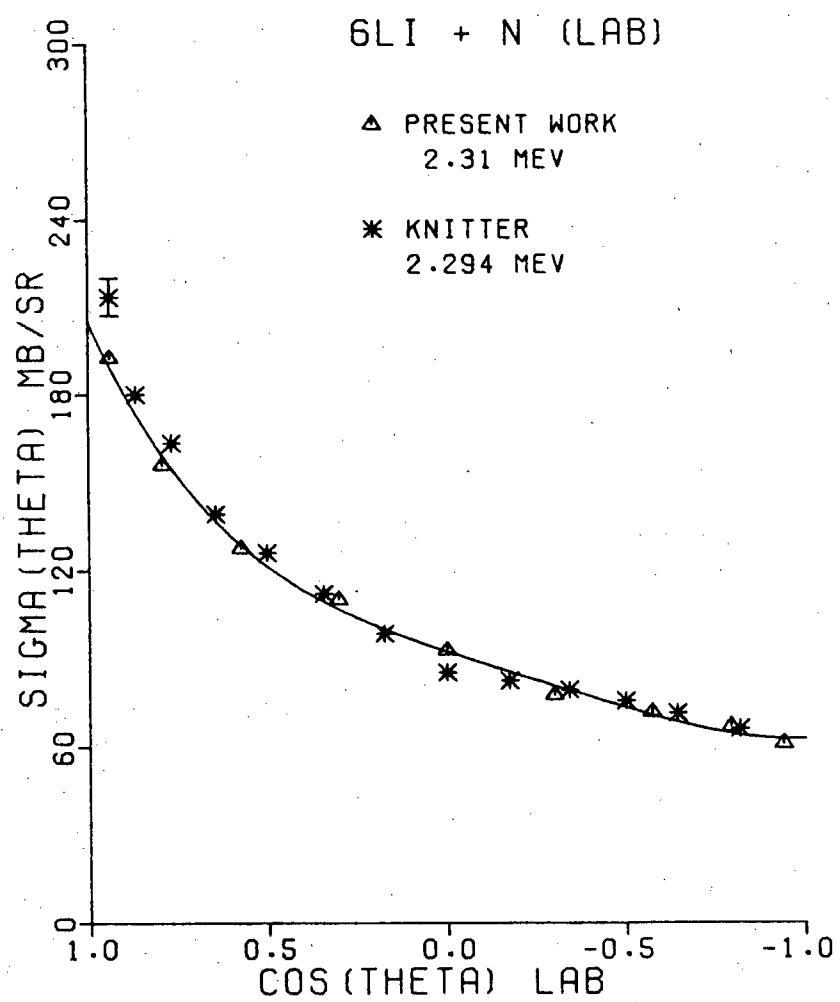


Figure 15. A comparison of the present ${}^6\text{Li} + \text{n}$ elastic results at 2.3 MeV with the measurements of Knitter *et al.*¹⁰.

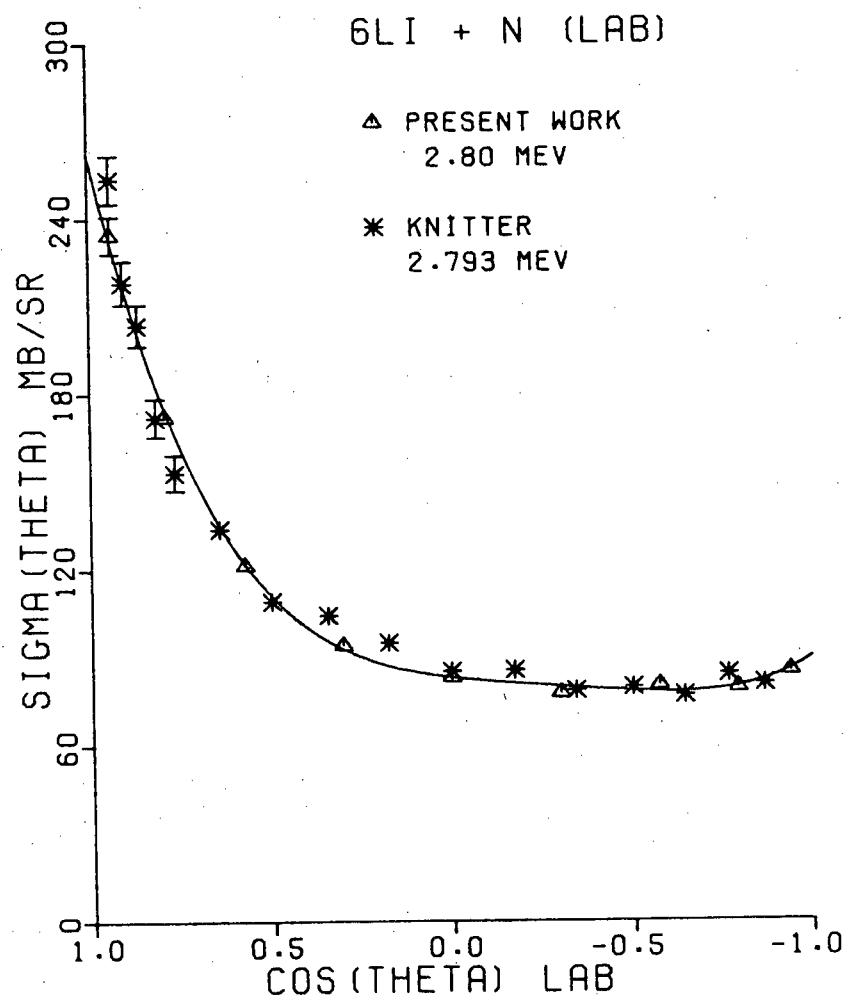


Figure 16. A comparison of the present ${}^6\text{Li} + \text{n}$ elastic results at 2.8 Mev with the measurements of Knitter *et al.*¹⁰.

D. $^{10}\text{B} + \text{n}$ Differential Cross Sections

The data for elastic scattering from ^{10}B for $E_n = 4\text{-}8$ MeV have been described in previous reports and appeared in final form in Nucl. Sci. Eng. 65, 65 (1978).

E. $^{11}\text{B} + \text{n}$ Differential Elastic Scattering Cross Sections

During the past year new differential elastic scattering cross sections on ^{11}B were measured at 24 incident neutron energies from 2.00 to 4.00 MeV at nine angles per energy. These data supplement over 60 differential cross section measurements taken at Ohio University during the past three years. As reported previously,¹¹⁾ the earlier data measured by Nelson, et al.¹²⁾ in the 2 to 4 MeV region were found to be in error by 5 to 15% in normalization at some energies. This led to difficulties in the R-matrix fitting in this region as outlined in last year's progress report.¹¹⁾ The new measurements were completed in February and the final data are ready for publication. Inclusion of this data into our $^{11}\text{B} + \text{n}$ differential cross section file* now gives approximately 160 accurate differential cross sections for neutrons on ^{11}B from 75 keV to 8.03 MeV.

A new R-matrix analysis of $^{11}\text{B} + \text{n}$ from 0 to 8 MeV is now underway using the new data in the 2 to 4 MeV region. The R-matrix analysis utilizes ORMAP, the Ohio (University) R-matrix Analysis Program, which is a multilevel-multichannel code. It is expected that this analysis on $^{11}\text{B} + \text{n}$ will be completed by September 1978 and submitted for journal publication by early fall. A report containing the new $^{11}\text{B} + \text{n}$ elastic differential cross sections from 2 to 4 MeV will also be available to the data centers by September 1978.

*This file contains data other than that measured in this program, see Report COO-2490-6.³⁾

This essentially completes the neutron elastic differential cross section measurements program on ^{11}B at Ohio University. As the integrated elastic cross section for neutrons on ^{11}B is only 75-85% of the total cross section for incident neutron energies greater than approximately 4.5 MeV, the next effort on ^{11}B will be to measure the neutron inelastic cross section primarily above 4.5 MeV neutron energy. These measurements are scheduled to begin in late fall 1978.

F. $^{13}\text{C} + \text{n}$ Differential Elastic Scattering

As a collaborative effort with G.F. Auchampaugh of Los Alamos Scientific Laboratory we measured neutron differential elastic scattering cross sections for ^{13}C at 9 angles from 20° to 160° and 22 energies from 1.57 MeV to 6.5 MeV. Previous to this no differential cross section measurements had been reported in the literature. Also, no definite spin and parity assignments in ^{14}C had been made at energies above the neutron separation energy, except the 2^+ state at 8.32 MeV as seen in Fig. 17. The scattering sample was 98% ^{13}C with most of the remainder being ^{12}C . The sample was fabricated at LASL by pressing 41 g of the graphite in powder form into a cylinder 3.57 cm dia. and 3.23 cm long. The method of measurement was the same as that used in our previous experiments, i.e. it is based on the well-established method of placing the detector in the neutron beam directly from the source to determine the flux incident on the scatterer, where the relative variation in efficiency with energy is determined from the variation with energy of the ratios of yields for the $\text{T}(\text{p},\text{n})^3\text{He}$ reaction. The flight path was 3.6 meters for this experiment. The data were corrected for multiple scattering effects by use of the Ohio University reprogrammed version of the monte carlo code MONTE SAMPLE. Fig. 18 shows the preliminary results of this experiment in the form of the Legendre polynomial expansion coefficients for the differential elastic scattering cross sections (center-of-mass system) as a function of laboratory energy where the solid curve connects the data points.

A second series of measurements was performed from 1.25 to 4.5 MeV just recently. These extended the lower limit down into the s-wave-dominated region, filled in the gaps to more clearly delineate the structure observed in the first survey experiment shown here, and provided repeat check points.

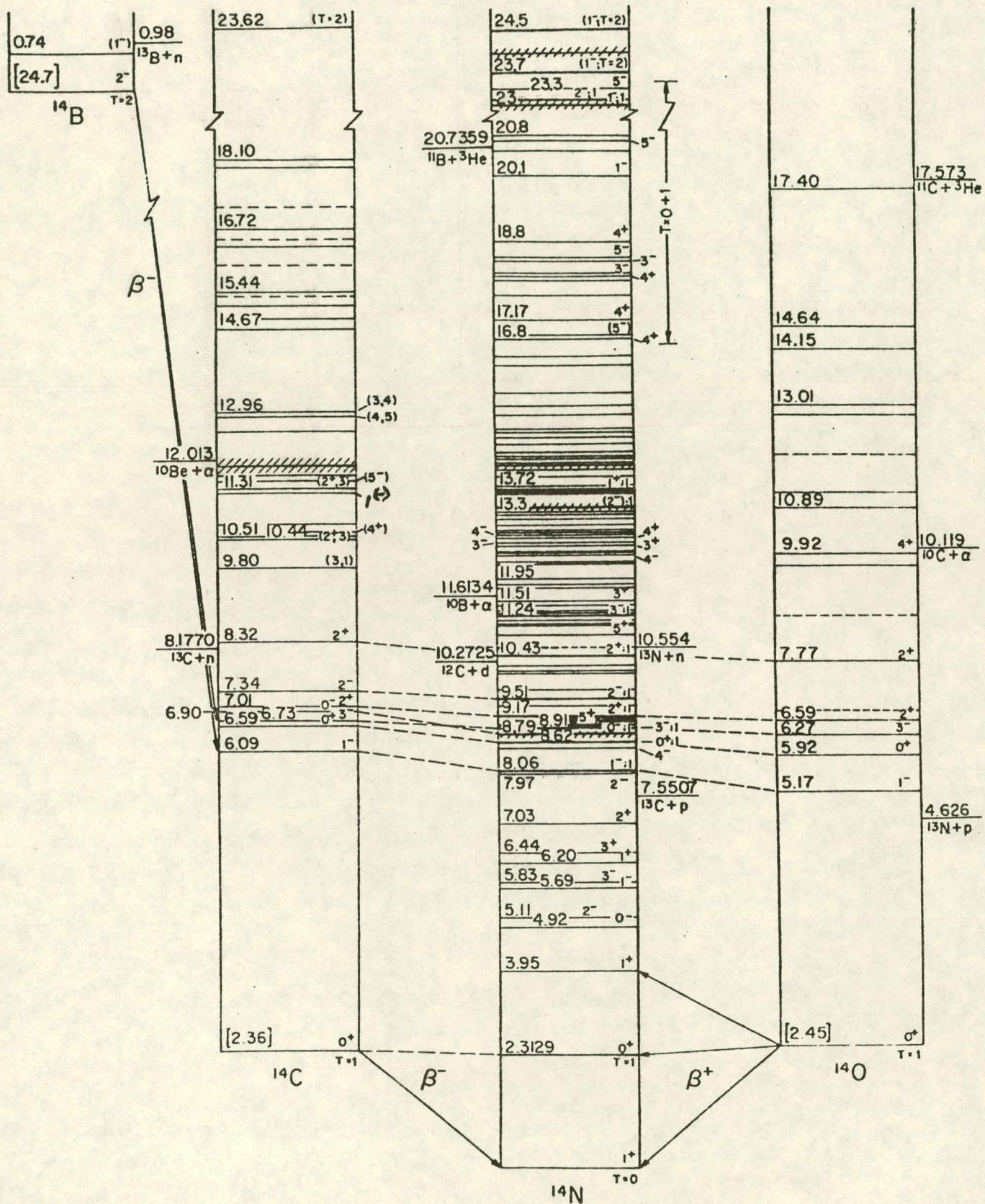


Figure 17.

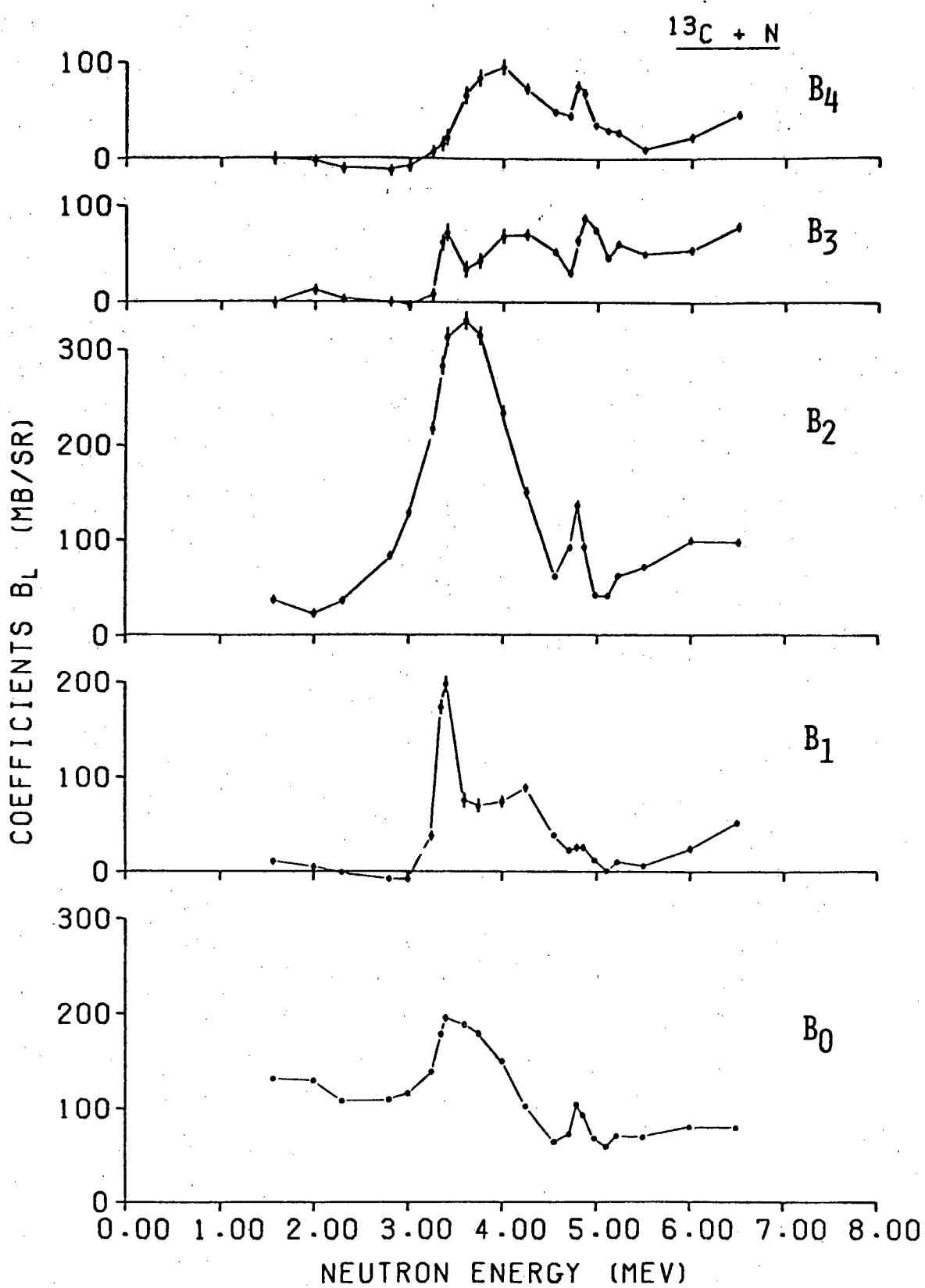


Figure 18.

There has not been time to reduce all the data of this second series on ^{13}C for presentation in this report, however examination of the preliminary results allow us to draw some tentative conclusions which will be subjected to corroboration in the final analysis with the complete data set.

Since our most convenient energy spread with high counting rates is 40-60 keV our initial investigations naturally focus on resonances of $\Gamma \geq 60$ keV. Resonances of rather large Γ in the $^{13}\text{C} + \text{n}$ channel would imply states having terms in their wave functions of relatively simple configuration. Thus the proper identification of the J^π , E_λ , $\gamma_{\lambda c}$ and other properties of the broader states may be directly related to theoretical calculations of the shell model in the continuum which treats this as two neutrons outside of a ^{12}C core. Resonances having large widths for elastic scattering of neutrons from ^{13}C would be expected to correspond to states in ^{14}C having an appreciable amplitude for a neutron coupled to ^{13}C in the ground state.

A region of particular interest in this regard is that of the very broad "hump" between 3 MeV and 4.5 MeV which is obviously a composite of several fairly broad resonances. Fig. 19 shows an initial R-matrix fit to the data using the Ohio University R-matrix program ORMAP described in Ohio University Report COO-2490-6 where it was applied to $^{11}\text{B} + \text{n}$.

The radius parameter and constant terms $(R_{c,c}^0)^{J^\pi}$ of the R-matrix were varied over wide ranges to establish the best fit to the non-resonant differential cross sections throughout this region. The 0^- and 1^- bound states have large amplitudes for the configurations $(1p_{1/2}, 2s_{1/2})_{0^-} 1^-$ and produce a very large s-wave scattering contribution below $E_n \sim 1.5$ MeV. Using values of $\gamma_{\lambda c}$ for the bound 0^- and 1^- states that gave approximately the correct shape and magnitude of the low-energy total cross section, together with variations of the $(R_{c,c}^0)^{J^\pi}$, it was determined that a value of 4.5 F for

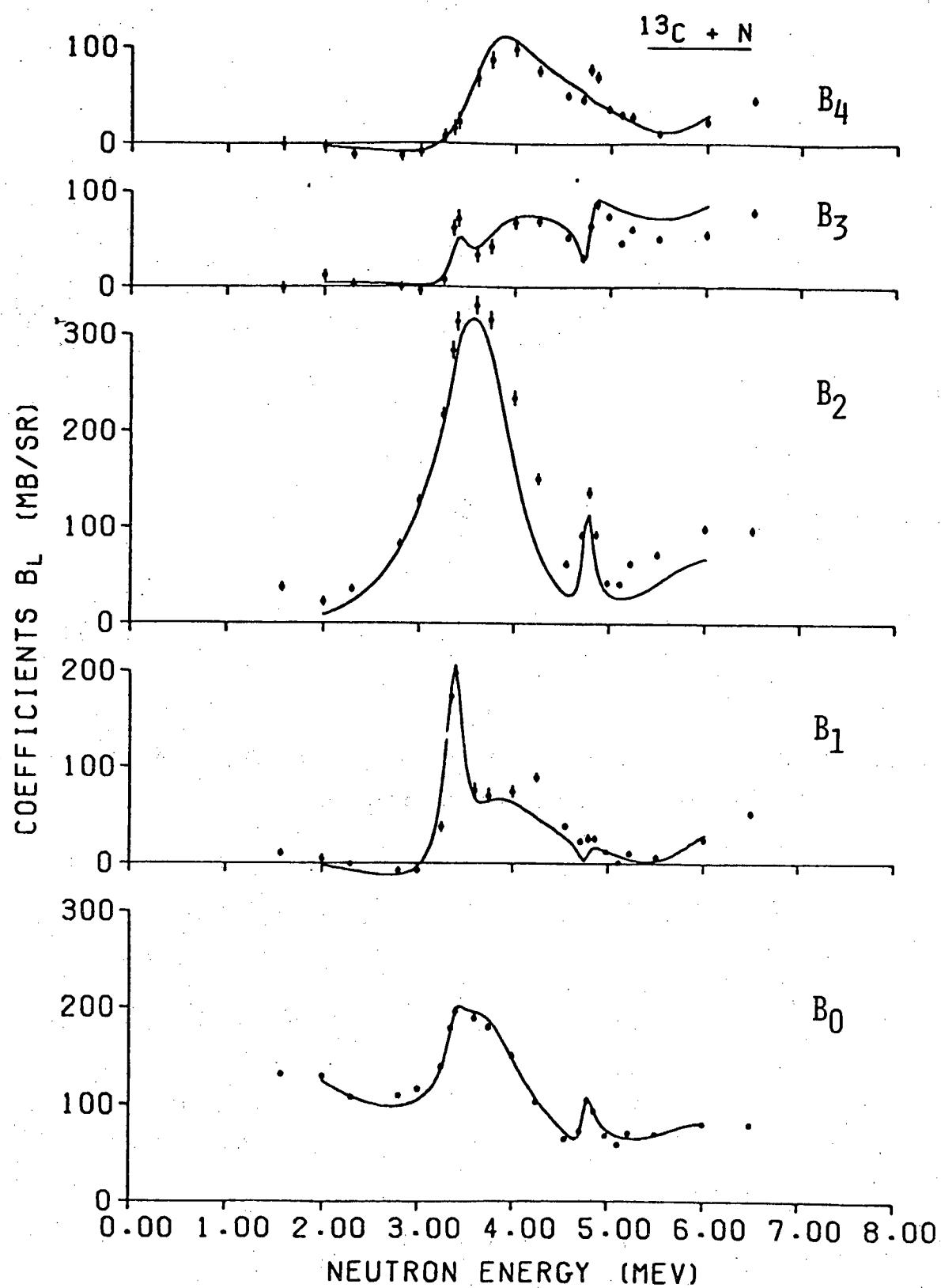


Figure 19.

the radius parameter gave the best fit to the preliminary data. The curve in Fig. 19 is based on a 1^+ state assumed at $E_n \sim 3.4$ MeV, a very broad 1^- state at $E_n \sim 3.5$ MeV and a fairly broad 2^- state at $E_n \sim 3.8$ MeV. However, the lack of fit in B_1 and B_2 on the upper side of the broad hump indicates that our calculations are not yet correct. Fig. 20 shows the effect of the addition of a 1^- state near $E_n \sim 4.1$ MeV. While this improved some areas of the fit, substantial discrepancies still remain in others. With the inclusion of the recent second series of measurements, together with a more detailed experiment scheduled for the future from 4.5 MeV up to ~ 8 MeV, we hope to determine quantitatively a considerable amount of the structure information in ^{14}C .

Some semi-quantitative observations can, however, be made at this point. Our tentative assignment of a 1^+ state at $E_n \sim 3.4$ MeV ($E_x \sim 11.3$ MeV) is consistent with earlier very tentative assignments of a state in this region as observed by other reactions. From the $^9\text{Be}(^6\text{Li},\text{p})^{14}\text{C}^*$ reaction Ajzenberg et al.¹³⁾ assign a state as $J = 1$ at $E_x = 11.3$ MeV with probable negative parity. Kaschl et al.¹⁴⁾ assign a state at $E_x = 11.29$ MeV as 1^+ from the reaction $^{15}\text{N}(\text{d},^3\text{He})^{14}\text{C}^*$. Neither of the two earlier states appears to have been very firm, however we feel our 1^+ preliminary assignment will be confirmed when all of the recent data have been included in the R-matrix fitting. Further corroboration of this may be seen by comparing the analog region of ^{14}N , i.e. near $E_x(^{14}\text{N}) \sim 13.6$ MeV ($= 2.3$ MeV + $E_x(^{14}\text{C})$). As shown in Fig. 17 there is a 1^+ , $T = 1$ state in ^{14}N at $E_x = 13.7$ MeV, within 100 keV of the expected value. Near that state in ^{14}N is also a $T = 1$ state tentatively assigned as (2^-) . While the 1^+ and 2^- states occur in reverse order in the two nuclei they do fall very close to expected energies in their respective nuclei in order to be possible analogs. Fig. 17 shows other reverse-order analogs at lower energy. Furthermore these two are the only $T = 1$ states shown in that entire region of ^{14}N ,

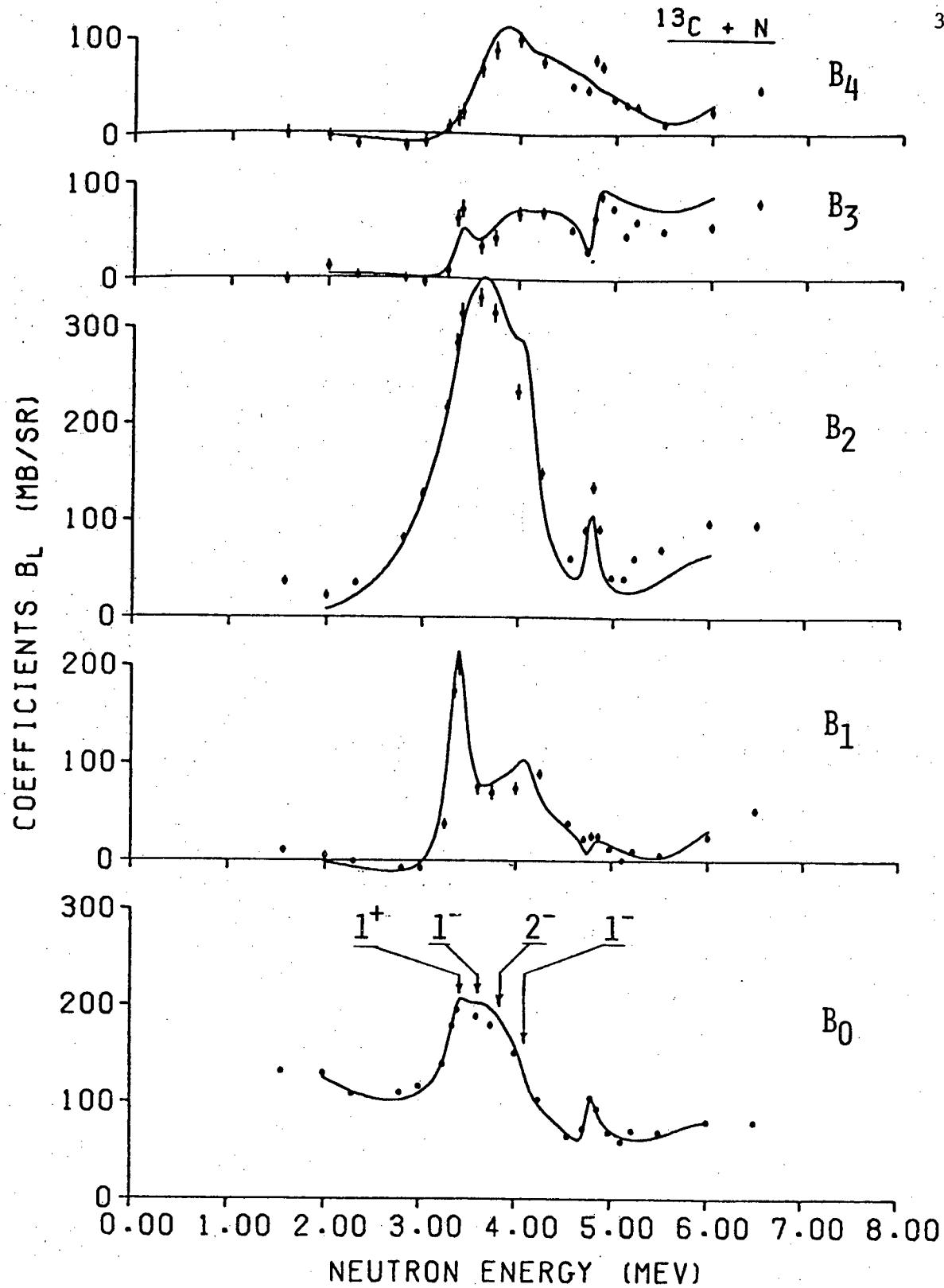


Figure 20.

and have similar widths for the possible analog states.

Another interesting point is that the very broad 1^- state at $E_x = 11.4$ MeV in ^{14}C which we deduced from these preliminary data has nearly all its width in the $d_{3/2}$ channel. The nearby broad 2^- state was found in this analysis to contain equal amounts of $d_{3/2}$ and $d_{5/2}$ strength. Together they may represent a substantial part of the strength of the 1^- , 2^- multiplet formed by $(^{13}\text{C}_{\text{g.s.}}, 1d_{3/2})$, a rather simple configuration, hopefully amenable to theoretical prediction. That these states (or at least the 1^- state) form a major part of the $1d_{3/2}$ single particle strength in ^{14}C is also supported by examination of the $1d_{3/2} - 1d_{5/2}$ spin-orbit splitting in ^{13}C .

The difference between the $1d_{5/2}$ state ($E_x = 3.85$ MeV) and the $1d_{3/2}$ state ($E_x = 8.2$ MeV) is ~ 4.3 MeV. In ^{14}C the $(^{13}\text{C}_{\text{g.s.}}, 1d_{5/2})_{2^-, 3^-}$ multiplet is centered near $E_x \sim 7$ MeV, so one would expect to find substantial strengths for $(^{13}\text{C}_{\text{g.s.}}, 1d_{3/2})_{1^-, 2^-}$ centered near ~ 11.3 MeV or so, which we do.

Very recent $^{12}\text{C}(t, p)^{14}\text{C}^*$ results¹⁵⁾ have come to our attention and we are attempting to compare our results with these where possible. However, those investigators indicate they would observe mainly states of $\Gamma \lesssim 20$ keV or so whereas we observe broader states. Also many of the configurations of states observed in that reaction are quite different from those we would observe because of the strong preference for pairing in that reaction, whereas one of the two neutrons outside of ^{12}C in our case is in the ground state, $1p_{1/2}$, at least in the entrance channel.

These results were presented at the last Washington Meeting of the American Physical Society, April, 1978.

G. Experimental and Computational Improvements

1. Pulse Shape Discrimination Improvements

In our earlier elastic scattering work, the neutron detector consisted of an 8 in. diameter by 2 in. thick NE224 liquid scintillator coupled to an RCA 4522 photomultiplier tube. New detectors consisting of 4½ in. diameter by 2 in. thick NE213 liquid scintillators coupled to RCA 4522 photomultiplier tubes are now being used. The change to NE213 was prompted by the excellent pulse shape discrimination properties of this liquid. We have also abandoned the ORTEC 458 pulse shape discriminator in favor of the following method: Dynode signals from the detector preamplifier are amplified and shaped by an ORTEC 460 delay line amplifier and the bipolar output routed to an ORTEC 420 timing SCA. This ORTEC 420 is used to set the system bias for the neutron detector. The ORTEC fast 420 output is then used to START a time-to-amplitude converter (TAC). The detector anode signal is routed to a CANBERRA 1428 constant fraction discriminator. The output of this discriminator is delayed ($\approx 1 \mu s$) and then used to STOP the TAC. Using the new detectors, the time separation between the neutron and gamma groups on the TAC output has been greater than 30 nsec with the neutron bias as low as 450 keV. A typical PSD spectrum is shown in Figure 21. This pulse shape discrimination method has been used in our latest $^{13}\text{C} + \text{n}$ elastic and $^7\text{Li} + \text{n}$ inelastic measurements with excellent results.

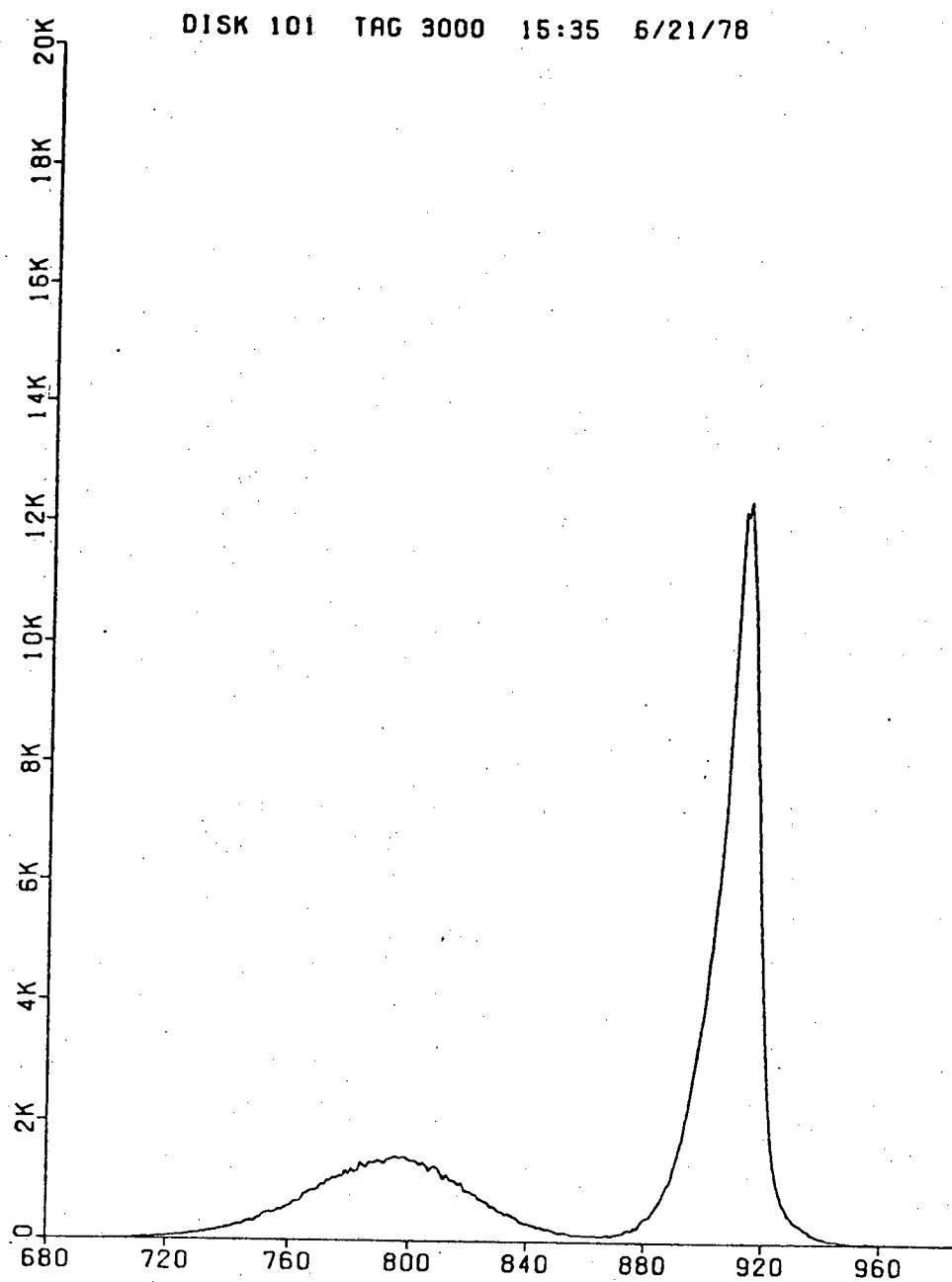


Figure 21. Typical pulse shape discrimination spectrum. The neutron detector bias here is about 450 keV.

2. Computations

We have recently acquired a new Tektronix 4025 graphics display terminal for use in analyzing the neutron data measured in this program. This graphics display terminal is microprocessor based and contains internally 32K of graphics memory and 32K of alphanumerics memory. The terminal presently is hard wired to the Ohio University IBM 370/158 computer system via a 1200 baud line. A 2400 baud line is scheduled for September 1978.

Previously all data reduction and analysis was handled by the laboratory's IBM 1800 computer. This older generation machine is adequate for data reduction purposes but highly unsatisfactory for R-matrix analysis of the data. The Laboratory's computer has only 13K of variable core left for general programming and therefore any significant calculation requires use of many overlays and other time consuming techniques, and generally has placed limits on the use of levels and channels in the R-matrix analysis of neutron data.

The Ohio University R-matrix analysis program, ORMAP, was written specifically for analyzing the neutron elastic cross sections measured on the light nuclei. It is a multilevel, multichannel code with no restriction on the number of levels or channels and a version which will allow full potential of the code is now running on the university IBM 370/158. Use of the graphics display terminal allows the running of ORMAP effectively in interactive mode as it runs approximately 50 times faster on the larger computer. Therefore, a terminal session of a few hours now allows the work previously completed in several weeks on the older machine. Also, the Monte Carlo multiple scattering code used to correct the neutron scattering data is handled through this terminal with an improvement in performance of approximately five times. This graphics display terminal hard wired via high speed line to the larger main frame

university computer has yielded orders of magnitude improvement in our computational effort in analyzing neutron scattering data.

III. Magnetic Quadrupole Spectrometer for (n,z) Reactions

At this writing, the development and assembly of the Ohio University quadrupole triplet spectrometer is progressing rapidly. The magnetic lenses and power supplies were obtained from Cornell early in 1978.

The Lawrence Livermore Laboratory magnet optics computer programs were used to evaluate several possible design considerations. The final design permits two possible configurations of the magnets: a standard radiator-to-detector flight path of 3.4 m and a long flight path of 4.5 m. The long-flight-path option will be valuable in those cases in which very low background is required and/or better particle identification is needed. The long flight path could also be used if it is desired to measure the charged particle energy by time of flight.

A mechanical carriage has been designed to position the spectrometer at the standard beam-tube height. A mechanical design specialist was hired as a consultant to prepare the detailed design drawings for the carriage. Angular distributions will be measured by rotating the spectrometer (on air bearings) about a vertical axis through the radiator. The air pads, steel I-beams and other materials for the carriage have been received and construction is nearly complete.

The magnetic lenses, power supplies, and current regulators have been tested. They were received from Cornell in good working order.

The spectrometer vacuum system, target changer, detector housing, etc. have been designed, and many components have been constructed or purchased. The first bid on the hyperpure germanium detector has been received.

The computer codes TRANSPORT and TURTLE have been obtained from SLAC and placed in operation on the Ohio University computer system. This was an important step since many details of the spectrometer design and operation

depend on the ability to perform such calculations locally.

In summary, construction of the spectrometer is progressing according to schedule. The first experiments should be performed in the fall of 1978.

IV. Scientific Publications, Papers Presented, Colloquia, Seminars

A. A paper of the following title was published in Nuclear Science and Engineering 65, 65 (1978); "Differential Elastic Scattering Cross Sections of Boron 10 for Neutrons of 4 to 8 MeV Energy", H.D. Knox, R.M. White and R.O. Lane.

B. The following is an abstract of a paper submitted to Nuclear Science and Engineering: "Differential Scattering Cross Sections of Lithium 6 and Lithium 7 for Neutrons of 4 to 7.5 MeV Energy", H.D. Knox, R.M. White and R.O. Lane.

Abstract

Differential cross sections for neutrons scattered elastically from ^{6}Li and ^{7}Li have been measured at 14 incident neutron energies between 4 and 7.5 MeV. For ^{6}Li , neutrons inelastically scattered from the 0.478 MeV level were not resolved from the elastic group and have been included with the elastic group in calculating the cross sections. The present ^{6}Li data are in good agreement with the ENDF/B-IV evaluation while the present $^{7}\text{Li}(n, n_0+n_1)$ data are generally larger than the corresponding ENDF/B-IV evaluation particularly at forward angles.

C. A report COO-3490-8 of the following title was published in June, 1978: "Differential Scattering Cross Sections of ^{6}Li and ^{7}Li for Neutrons of 4 to 7.5 MeV Energy", by H.D. Knox, R.M. White and R.O. Lane.

This report was similar to the article above submitted to Nuclear Science and Engineering, but contained extensive numerical data.

D. The following is an abstract of a paper presented at the Washington, D.C. Meeting, April, 1978: "Differential Cross Sections and R-Matrix Analysis of 1.5 to 6.5 MeV Neutrons Scattered from ^{13}C ", R.O. Lane, R.M. White,

H.D. Knox and G.F. Auchampuagh,

Abstract

Neutrons produced by the $T(p,n)^3He$ reaction with the Ohio University Tandem Van de Graaff were scattered from a 41 g enriched sample of ^{13}C (98.0%). Nine angles were measured from 20° to 160° by T.O.F. methods with a 3.6 meter neutron flight path. Over 30 angular distributions were obtained at energies from 1.5 to 6.5 MeV where no data have been previously reported and where significant resonance structure exists. Multiple scattering corrections are presently underway. The data are being analyzed with the Ohio University program ORMAP, a multichannel, multilevel R-matrix code. New J^π assignments and level parameters for several states will be discussed.

E. The following colloquia and seminars were given by members of the staff:

1. "Study of Light Nuclei at Ohio University", Physics Department Colloquium, West Virginia University, April 20, 1978--R.O. Lane.
2. "Study of the Higher Excitation States of ^{12}B via the Scattering of Neutrons from ^{11}B ", E-Division Colloquium, Lawrence Livermore Laboratory, July 12, 1978--R.M. White.
3. "Study of the Higher Excitation States of ^{12}B via the Scattering of Neutrons from ^{11}B ", Los Alamos Scientific Laboratory, July 18, 1978--R.M. White.

F. The Principal Investigator participated with Steven Grimes in the recent April 1978 Meeting of the DOE/NDC Committee at the DOE Headquarters Building at Germantown, Maryland. Dr. Grimes presented a talk showing the plans for the new magnetic quadrupole spectrometer to be constructed at Ohio University this coming year under the leadership of Steven Grimes while on sabbatical leave from Livermore.

G. The following is an abstract which has been submitted for presentation at the Asilomar, California Meeting, November 1978: "Differential Cross Sections of 2.3 and 2.8 MeV Neutrons Scattered from ${}^6\text{Li}$ and ${}^7\text{Li}$ ", H.D. Knox, R.M. White, D.A. Resler, P.E. Koehler and R.O. Lane.

Abstract

Neutrons from the $\text{T}(\text{p},\text{n}){}^3\text{He}$ source reaction were scattered from highly enriched samples of ${}^6\text{Li}$ (99.30%) and ${}^7\text{Li}$ (99.99%). Differential elastic and inelastic (0.478 MeV level) cross sections for neutrons scattered from ${}^7\text{Li}$ and differential elastic cross sections for neutrons scattered from ${}^6\text{Li}$ 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 ${}^6\text{Li} + \text{n}$ inelastic measurements are the first to be reported in this energy region. The present results show the ${}^7\text{Li} + \text{n}$ inelastic cross section to be isotropic at these energies. Comparison of the present ${}^6\text{Li} + \text{n}$ elastic results with previously reported experiments will be made.

V. Scientific Staff

Post Doctorates: Harold D. Knox
Roger M. White

Students, Part-time undergraduates:

Steven T. Lane
Paul E. Koehler
David A. Resler

During the three quarters of the academic year the Principal Investigator
spent 30% of his time on the contract and spent 100% during the fourth quarter.

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