Angular distributions of neutrons elastically scattered from $^{12}$C were measured from 1.8 to 5.0 MeV at intervals of 0.5 MeV and at incident neutron energies between 20 and 100 deg. The angular distribution measurement were performed relative to those from the $^{12}$C(n,n) reaction. In addition, total neutron cross sections were deduced from monoenergetic (AE=2 keV) neutron transmissions in the energy range 1.5-5.0 MeV. The experimental results were interpreted in terms of a multi-level R-matrix analysis including considerations of previously reported cross sections and polarizations. The resulting R-matrix parameters were compared with the Yale values deduced from observed scattered neutron polarizations. The measured values and analysis suggest physically consistent standard total and scattering cross sections readily referenced in measurement applications.

(Nuclear reaction $^{12}$C(n,n)$^{12}$C; measured $\sigma_{\gamma}(E)$, $E=1.5-5.0$ MeV,$\varphi_{\theta}(\Omega)$, $E=1.8-4.0$ MeV, $\theta_{lab} = 20^\circ$ to $160^\circ$; R-function analysis).

**Introduction**

Studies of the $^{12}$C+n system play an important part in the design of nuclear energy systems, the development of neutron flux calibration standards and the understanding of nuclear structure. In particular, the $^{12}$C(n,n)$^{12}$C reaction is of great importance for the construction of moderators, reflectors and fuel-structural elements in both fission and fusion powered reactors. In addition, the total and differential scattering cross sections of $^{12}$C provide convenient reference standards for neutron flux measurements and at the total cross section of $^{12}$C would allow one to use $^{12}$C directly as a reference standard rather than the usual hydrogen standard which is often employed in the form of a hydronium ($\text{H}_2\text{O}$) mixture. Moreover, certain well-defined resonances in the total cross section of $^{12}$C are widely used for energy calibration standards.

The $^{12}$C+n system is well-suited for studies of basic reaction mechanisms and nuclear structure, since the $^{12}$C(n,n)$^{12}$C reaction is dominated by four major resonances below 5 MeV. This reaction has been extensively analyzed using the R-matrix formalism. The most notable analysis was based upon an interpretation of neutron polarization data over the energy range 2 to 5 MeV and the total cross section was predicted to be 0.5 to 5 MeV. The validity of the total cross section prediction was difficult to assess, since several measured total neutron cross section sets were not consistent, particularly in the 2 to 3 MeV region. In addition, the p-wave phase shifts were deduced from an analysis of the polarization data, which are in disagreement with those found from an interpretation of angular distribution measurements.

In view of the importance of the $^{12}$C(n,n)$^{12}$C reactions, we have measured the total cross section of $^{12}$C from 1.5 to 5.0 MeV. In addition, we have measured the angular distributions of neutrons scattered from $^{12}$C throughout the energy region 1.8 to 4.0 MeV and at 20 to 90 angles between 20° and 160°. These measurements were interpreted in terms of a multi-level R-function analysis in which the R-function parameters were fitted to the observed angular distributions and the total cross section and polarizations were predicted. The final parameters are found to be in good agreement with those reported by the Yale group, and hence, provide a unified description of the $^{12}$C+n system below 5 MeV.

**Total Neutron Cross Sections**

The total neutron cross section measurements employed a variation of the monoenergetic source techniques discussed by Miller. The neutron source was the Li(p,n) reaction with the neutron energy determined from the kinematics and the reaction threshold of 1.8815 MeV. The incident neutron energy spread was approximately 2 keV. All carbon samples were fabricated out of high-purity, pile-grade graphite. The neutrons from the source traveled along a 5-m, well-collimated flight path before being detected in a liquid scintillator. The pulsed source provided proton bursts with widths of 1 ms and conventional time-of-flight techniques were employed in order to assure that the detector response was confined to the primary neutron-source group and to reduce the background. In-scattering corrections were found to be negligible.

**Elastic Neutron Scattering Cross Sections**

The scattering measurements were made using the time-of-flight spectrometer and the 30-angle detector system in conjunction with the Li(p,n) pulsed neutron source available at the Argonne Tandem Neutron Laboratory. Scattered neutron flight paths were 5 to 6 meters and velocity resolutions ranged from 0.4 to 0.8 nsec/meter, incident neutron resolutions were 20 to 50 keV. The scattering angles were determined relative to an accuracy of 0.1 deg. The angular zero was determined to 0.5 deg. by observing the energies of neutrons scattered from the hydrogen of a CH$_2$ sample both left and right of the center line. The relative efficiencies of these detectors were determined by observation of the scattering of neutrons from hydrogen in a CH$_2$ sample. Subsequently, the normalization of the relative detector efficiencies was determined relative to the well-known H(n,p) scattering cross section. The calibration of each of the 10 detectors was essentially independent and repeated at each of the numerous measurement periods. All of the scattering results including those associated with the normalization of the detector.

**Experimental Methods**

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**Angular Distributions**

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The total neutron cross sections were measured from 1.5 to 5.0 MeV with incident energy resolutions of 2 to 5 keV and at energy intervals which were sufficiently small to define the previously reported structure in the n + 12C system. The present results are outlined and compared with the work of Schwartz et al. in Fig. 1. At the 2.08 MeV resonance the present resolution is better than that of Schwartz et al., but not as good as that reported by Cierjacks et al. Near 5.0 MeV the present resolutions are superior to those of either ref. 6 or 7. In the energy regions where the excitation function is slowly varying with energy, the magnitudes of the present measurements agree very well with those of Schwartz et al. with an average deviation between the two sets of 3.4 percent. This deviation was generally random in sign with possibly a slight tendency for the present results to have lower average magnitudes. Over wide energy ranges, the present results are remarkably lower than those of ref. 7. The results of Foster and Glasgow and, to a lesser extent, Paumon et al. and Buckelman et al. are consistent with the present values. Two prominent and narrow resonances were observed at 2060 ± 5 keV and 2211 ± 5 keV, respectively. These observed energies are in very good agreement with those reported by Schwartz et al., Davis and Noda, and that determined from 11B(d,p)12C reaction studies.

Generally, the present results, together with lower energy values previously reported from this laboratory, strongly support the results of Schwartz et al., obtained with an alternative method. Over the range 0.1 to 5.0 MeV, the discrepancy in energy-average normalization between the two results is 3-2 percent.

Elastic Neutron Scattering

The elastic neutron scattering results were obtained in more than ten measurement periods distributed over four years. Some of these results are illustrated in Fig. 2. The individual distributions contained from 16 to as many as 90 differential values. The differential cross-section uncertainties varied from 5 percent to as much as 20 percent including relative and normalization contributions. The total average deviation of the measured values from Legendre polynomial fits was 6.5 percent. This value is consistent with the individual uncertainties. The average deviation between the total cross section, determined from polynomial fits to the observed angular distributions, and those values reported by Schwartz et al. was found to be small (3.2%) compared to the uncertainties of the two measurements. Some impression of the general quality and scope of the present work can be obtained from Fig. 3.

There have been several previously reported measurements of elastic neutron scattering from carbon. The most recent are those of Lane et al. and Galati et al. The latter work is particularly detailed and is reported at incident energies near those of the present work. The Galati et al. results compare favorably with many of the present values as illustrated in Fig. 3.

R-Function Analysis

A five-level R-matrix analysis was used to fit the observed angular distributions between 1.5 and 4.5 MeV including resonance states in the n + 12C system at 2.076(d3/2), 2.92(d5/2), 3.50(d7/2), and 4.20(f5/2) MeV. In addition, bound states at -1.68(s1/2) and -1.270(p3/2) MeV were included in order to achieve a good description of the angular distributions. The results for the range 2 to 5 MeV are compared with many of the present values in Fig. 3.
Fig. 2. Present measured (circles) and calculated (curves) differential elastic scattering cross sections of carbon.

Elastic scattering is the dominant process in the $^6$Li $^{12}$C reaction at energies below 4.0 MeV, since the R-matrix reduces to the R-function:

$$ R^m_{mn} = \sum \gamma_{\lambda \mu}^2 \frac{\gamma_{\lambda \mu}^2}{E_{\lambda \mu}} + R^\gamma_{\lambda \mu} $$  \hspace{1cm} (1)

where $\gamma^2_{\lambda \mu}$ and $\gamma^2_{\lambda \mu}$ are reduced widths and level energies, respectively, for resonances $\lambda$ with orbital momentum $l$ and spin $J$. In addition to explicitly defined levels there is the contribution from distant levels, $\nu$, given by:

$$ R^\nu_{\lambda J} = \sum_{\mu=\lambda} \gamma_{\mu \lambda}^2 \frac{\nu_{\mu \lambda}}{K_{\mu \lambda} - E} $$  \hspace{1cm} (2)

Here $K_{\mu \lambda} >> 1$ and only two leading terms are significant:

$$ R^\nu_{\lambda J} = R^{o \lambda J} + R^{b \lambda J} \cdot \nu $$  \hspace{1cm} (3)

where

$$ R^{o \lambda J} = \sum_{\mu} \gamma_{\mu \lambda}^2 \frac{\nu_{\mu \lambda}}{K_{\mu \lambda} - E} \text{ and } R^{b \lambda J} = \sum_{\nu} \gamma_{\mu \lambda}^2 \frac{\nu_{\mu \lambda}}{K_{\mu \lambda} - E} $$

These approximations are applicable to the present case since $K_{\mu \lambda}$ is satisfied. The observables are computed from the collision function with the expression:

$$ U_{mn} = e^{-2i\phi} \frac{1 - R^{o \lambda J}(S_{\lambda \mu} - iP_{\lambda \mu})}{1 - R^{b \lambda J}(S_{\lambda \mu} + iP_{\lambda \mu})} $$  \hspace{1cm} (4)

where $\phi$, $P$, and $S$ are hard-sphere phase-shift, penetration factor and level-shift factor, respectively. The $P_{\lambda \mu}$ quantity is the boundary condition factor chosen to cancel the level-shift factor at the resonance energy, i.e., the same as used in the Yale analysis.

The analysis of all of the angular distributions was carried out concurrently for all measured angles and energies. The Yale $^3$R-matrix values were used as a starting point for the fitting procedures and the channel radius, $a$, was fixed at the Yale value of 4.61 fermis. The reduced width of the 2.07b MeV level is small (0.014 MeV), and consequently, was held constant in the present analysis. In addition, the p-wave bound-state reduced width (0.069 MeV) was not varied since it was determined from an analysis of the thermal total cross section. The p-wave bound state reduced width was fixed at 0.5 MeV since it provides a significantly better prediction of the neutron polarization. The analysis of the angular distribution was found to be relatively insensitive to the p-wave parameters over a fairly wide range of variation. However, the present analysis was sensitive to the s-wave parameters. The reduced widths of the 2.92, 3.5 and 4.20 MeV resonances were allowed to vary in the analysis. In addition, the $R_{\lambda J}$'s for all partial waves were varied in order to find the optimum fit to the angular distribution measurements.

Results of the R-Function Analysis

The final R-function parameters are compared with the Yale values in Table 1. The agreement between the two sets of parameters is excellent. This good agreement indicates that the present measurements are consistent with the neutron polarization work. Using the present values of the R-matrix parameters, the total cross section was predicted (see Fig. 1). The overall quality of the
K-function fit to the angular distributions is shown in Fig. 2. A detailed comparison of the K-function analysis with the data is given in Fig. 3. Finally, the R-function analysis is compared with measurements of neutron polarization in the energy range 2 to 5 MeV in Fig. 4.

Fig. 4. R-matrix predictions of the neutron polarization. The data were taken from the work of Holt et al. The dashed curve represents the R-matrix fit to the polarization data of ref. 6.

Conclusions

In conclusion, the total neutron cross section for the $^{12}$C(n,n)$^{12}$C reaction was measured in the energy range 1.5 to 5.0 MeV with an energy resolution of 2 to 5 keV. In addition, the angular distributions were measured at 20° to 90° angles between 20° and 150° throughout the energy region 1.8 to 6.0 MeV. These observations were interpreted in terms of the R-matrix theory and a self-consistent set of R-matrix parameters was found. These parameters were found to describe all observations of the $^{12}$C+n system throughout the energy range 0 to 5 MeV. It is hoped that these nuclear reaction mechanisms can now be interpreted in terms of the underlying nuclear structure. Finally, this R-function description of the $^{12}$C+n system provides a convenient means for simulating and extrapolating the neutron scattering from $^{12}$C by using extremely simple computer calculations.

References

This work supported by ERDA.
3. For example, see Technical Minutes of 6th INDC meeting, (1973).
20. R. Lane et al., Ohio University, Private Com.

TABLE 1

R-Function Parameters with $a=0.61$ fm

<table>
<thead>
<tr>
<th>$IJ$</th>
<th>$\lambda = 1$</th>
<th>$\lambda = 2$</th>
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<tbody>
<tr>
<td></td>
<td>$E_{lJ}$ (MeV)</td>
<td>$\gamma_{lJ}$</td>
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<td>$a_{1/2}$</td>
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</tr>
<tr>
<td>$d_{5/2}$</td>
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</tr>
</tbody>
</table>

*values are those from the Yale analysis which differ from the present values.