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DIFFERENTIAL CROSS SECTIONS FOR CARBON NEUTBON ELASTIC AND INELASTIC SCATTERING FROM 8.0 TO 14.5 MeV[1]

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Differential cross sections for fast neutrons scattered by carbon have been measured between 8.0 and 14.5 MeV in steps of 0.5 MeV. The angular distributions for elastic and inelastic scattering to the first excited level in ^{12}C have been obtained using the neutron time-of-flight facility of the Bruyères-le-Châtel Tandem Van de Graff accelerator. These results are compared with previous data for neutron energies up to 9 MeV and above 14 MeV. The agreement is fairly good. No other experimental contribution seems to have been reported at this time between 9 and 14 MeV. The theoretical interpretation is in progress.

A detailed knowledge of differential cross sections for fast neutrons scattered by carbon is required for calculations of neutron transport in reactor shielding materials. Moreover the main characteristics of resonance in the ^{13}C compound nucleus may be deduced from the study of the $^{12}C + n$ system.

In the past few years, elastic and inelastic scattering measurements have been made, some of them below a neutron energy of 9 MeV [1–3], the others around 14 MeV [4–5]. Our measurements were made, using the time-of-flight techniques, for incident neutron energies E_n from 8.0 to 14.5 MeV. This report presents the experimental procedure and the differential cross-section data for the elastic and inelastic scattering by the first excited level in ^{12}C.

Differential cross-section measurements were performed using the neutron time-of-flight facility of the Centre d'Études de Bruyères-le-Châtel. The experimental set-up is extensively described in another paper [6]; just a brief description will be given here.

The $D(d, n)^3He$ reaction was used to produce the incident neutrons. Deuterons were accelerated by the Tandem Van de Graaff accelerator. The beam was pulsed and bunched so that 1 ns bursts at a repetition frequency of 2.5 MHz were available. The average current was approximately 2.5 μA. A 3 cm long gas target with a cooled entrance Havar foil (5 μ thick) was used.

Monoenergetic neutron energies between 8.0 and 14.5 MeV correspond to incident deuteron energies from 5·1 to 11.6 MeV, respectively. In this range, the deuteron break-up reaction, whose threshold is 4.45 MeV, gives rise to an undesiderable neutron flux having

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a wide energy spectrum. However, the energy difference between monoenergetic neutrons and those coming from the break-up reaction is large enough to enable, in the whole range, scattering measurements for the ground state and the first excited (4.43 MeV) level in ^{12}C. The upper level have excitation energies higher than 7.66 MeV. Moreover, the inelastic scattering leaving the residual ^{12}C nucleus in these excited states contributes to the $(n, n'3\alpha)$ reaction which gives rise to continuous distributions of emitted neutrons.

The sample was a cylinder of pure carbon of $\emptyset = 2.5$ cm and $h = 3.0$ cm. It was suspended 15 cm from the centre of the gas cell for runs with detection angles greater than 20°. For measurements at 10°, the cell-to-sample distance was increased up to 24.5 cm to improve the shielding of the detector from direct neutrons.

Scattered neutrons were detected independently by four detectors. Each of them was composed of a NE 213 liquid scintillator, 12.7 cm in diam by 5 cm thick, mounted on a fast photomultiplier (XP 1040). Each detector was housed in a heavy shield of polyethylene and lead behind a 1.5 m long collimator of paraffin loaded with lithium and boron. Four 70 cm long shadow bars made of iron and lead reduced the background caused by direct neutrons coming from the target.

An auxiliary liquid scintillator with an n-γ discrimination was used, with the time-of-flight method, for monitoring the primary neutron beam. We also carried out the counting of the number of protons produced by the D(d, p)T reaction from the target. Those protons were detected by two diodes, each at 90° with respect to the beam, through windows in the cell. The neutron flux was determined using the n-p scattering cross section near 0° as a standard. It was measured with a proton recoil counter telescope having the same solid angle as that of the sample.

The flight-path lengths varied from 5 to 7 m, the detector angles ranging from 10° to 160°. The measurements have been made using standard time-of-flight techniques. To reduce unwanted events we proceeded to the neutron and gamma-ray pulse-shape discrimination. During the experiment, the linear pulse height from the time-to-amplitude converter was recorded simultaneously with the linear output of the photomultiplier dynode which is proportional to the recoil-proton energy. In the data reduction process, the time-of-flight spectra were sorted off line for two neutron-energy thresholds of 1.5 and 2.5 MeV, respectively. Background subtraction, peak stripping and peak area estimation were then carried out.

The energy dependence of the neutron detector efficiency was required for the determination of absolute cross sections. It was measured by two methods. In the first one, we counted direct neutrons from the target and used the reported values of the differentail cross sections for the D$(d, n)^3$He reaction. The second one is based on an $(n$-$p)$ scattering experiment using a polyethylene sample (1 cm diam by 4 cm height). The deduced cross sections for the two thresholds were in agreement within their statistical uncertainties.

Finally, our measurements were corrected for final sample effects (neutron-flux attenuation, multiple scattering and finite angular resolution) using an analytic method [7]. The overall accuracy between 5 % and 20 % varried with the detected neutron energy and with statistics.

Differential cross sections for the neutron elastic and inelastic scattering by the first excited level in ^{12}C were obtained at 14 incident neutron energies between 8.0 and 14.5 MeV in steps of 0.5 MeV. The incident neutron energy spread was constant over the whole range and equal approximately to 60 keV. The angular distributions were measured between 10° and 160° in steps of 10°. Our data, expressed in the centre-of-mass system, are plotted in Fig. 1. At neutron energies of $E_n = 8.5$, 9.0, 14,0 and 14.5 MeV they are

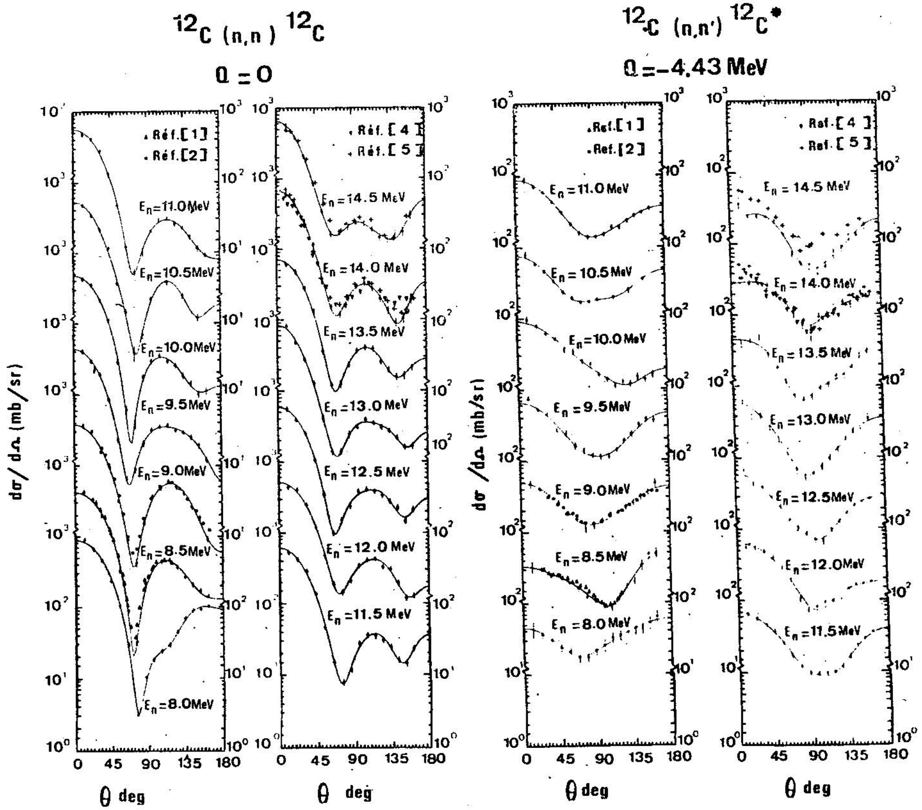

Fig. 1. Differential cross sections for the neutron elastic and inelastic scattering to the first excited level in ^{12}C.

compared to the previously reported data [1, 2, 4, 5]. The overall agreement is good. The solid curves are the results of least-squares fit to a Legendre polynomial expansion. The zero-order coefficients are used to deduce the integrated cross section. Their variations as a function of neutron energy are given in Fig. 2. The total cross section data of Cierjacks [8] are also plotted.

The consistency of our data with those from total, (n, α) and $(n, n'3\alpha)$ cross sections has been attempted. It was checked by computing the sum of the partial cross sections which must be equal to the total cross section. The (n, α) cross sections, from the threshold to 14.5 MeV, were taken from Ref. [9]. The $(n, n'3\alpha)$ reaction has no significant contribution to the total cross section up to 10 MeV (less than 30 mb). Between 10 and 12 MeV this cross section may be estimated from the non elastic data of Ref. [10]. Between 12 and 14.5 MeV measurements for the $^{12}C(n, n'3\alpha)$ reaction have been reported by Frye et al. [11]. Using our measurements and these data, we have plotted in Fig. 2 the sum of the partial cross sections. The good agreement between computed and measured total cross

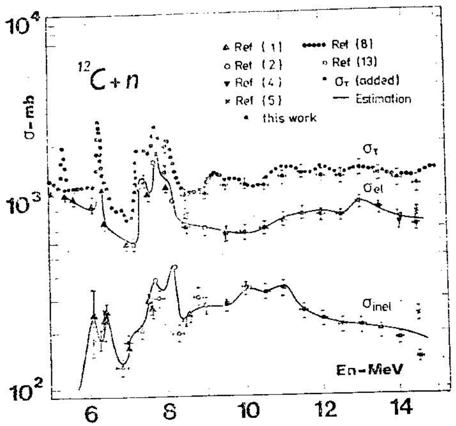

Fig. 2. Integrated cross sections for the neutron elastic and inelastic scattering to the first excited level in ^{12}C. Moreover the comparison between total and summed cross sections is given.

sections proves that for carbon up to 14.5 MeV a complete and consistent set of data is obtained.

The elastic scattering of neutrons by ^{12}C may be analysed assuming that the scattering amplitude is a sum of potential and resonant scattering terms. The optical-model analysis has been successful for proton elastic differential scattering by carbon above 12 MeV [12]. In the same way, we can assume that, for neutron elastic scattering by carbon near and above 12 MeV, far from resonances in ^{13}C, the potential scattering is prominent. At $E_n = 11.5$, 12.5, 14 and 14.5 MeV, the excitation functions present no resonance. The optical model code *SPI* was used to fit with the search routine the experimental elastic cross sections at these energies. We have, thus, found the following parameters:

Real potential: $V = (56.0 - 0.34\,E_n)$ MeV	Diffusivity: $a = 0.36$ f
Imaginary potential: $W_D = 8.65$ MeV	Diffusivity: $b = 0.27$ f
Spin-orbit potential: $W_{SO} = -5.15$ MeV	Diffusivity: $a = 0.36$ f
Radii: $R = R_D = R_{SO} = R_0 A^{1/3}$	$R_0 = 1.25$ f

The small value of the imaginary diffuseness parameter, about half the usual value for heavier nuclei, is very close to that found in the proton elastic scattering analysis [12].

The analysis of all the data is in progress. We assume that the scattered amplitude can be described by a sum of optical model and Breit-Wigner terms.

Differential cross sections for fast neutrons scattered by carbon have been measured between 8.0 and 14.5 MeV in steps of 0.5 MeV. We found good overall agreement with previously reported data over the ranges of overlap of neutron energies: below 9 MeV and above 14 MeV. The consistency of our data with the other partial cross sections and the total cross section has been proved. Thus, our measurements extend the region of complete and consistent data on neutron scattering by carbon up to 14.5 MeV.

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