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Disintegration of O^{16} and C^{12} by Fast Neutrons[†]

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Abstract

The disintegration of O^{16} and C^{12} by fast neutrons has been studied using a grid-type ionization chamber filled with CO_2-Ar or CO_2-Kr mixtures. Monoenergetic neutrons for studying the reactions from 5.0-8.8 MeV were produced with the $D(d,n)He^3$ reaction using a gas target. The α-particle group from the $O^{16}(n,\alpha)C^{13}$ reaction leaving C^{13} in its ground state was studied over the entire energy range. The excitation function showed 21 resonances corresponding to excited states in O^{17}. The cross section varied from 2-206 mb. The α-particle group leaving C^{13} in its 1st excited state was studied from 7.6-8.7 MeV, the cross section increasing from about 3-12 mb. Unresolved α-particle groups leaving C^{13} in its 2nd and 3rd-excited states were studied from 8.1-8.7 MeV, the cross section decreasing from an estimated 30-8 mb. The α-particle group from the $C^{12}(n,\alpha)Be^9$ reaction leaving Be^9 in its ground state was studied from 7.9-8.7 MeV. The cross section increased from 60-76 mb at 8.0 MeV and then decreased to 32 mb at 8.7 MeV.

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1. Introduction

The purpose of the present work is to extend the measurements of fast neutron reactions in oxygen and carbon which lead to charged particle emission. The only reactions energetically possible below a neutron energy of 9 MeV are those involving emission of an alpha particle. Although these reactions are possible in all the isotopes of oxygen and carbon, only those in the most abundant isotopes, O^{16} and C^{12}, are observed in the present experiment.

The cross section for the $O^{16}(n,\alpha)C^{13}$ reaction has been measured from threshold to a neutron energy of 4.2 MeV by Seitz and Huber[1)] using a parallel-plate ionization chamber filled with oxygen. Walton, Clement and Boreli[2)] have used a cylindrical proportional counter filled with carbon dioxide to measure the cross section for this reaction between 4.0 and 5.2 MeV. Ten resonances were observed in the excitation function for this reaction.

The $C^{12}(n,\alpha)Be^{9}$ reaction has been observed and its cross section measured at 14 MeV by Graves and Davis[3)].

In the present investigation the (n,α) reactions in O^{16} and C^{12} were studied with monoenergetic neutrons from 5.0 MeV to 8.8 MeV.

2. Experimental Method

The alpha particles emitted in the neutron disintegrations of oxygen and carbon nuclei were detected in a grid-type ionization chamber using electron collection. The chamber and associated experimental techniques have been previously described[4,5)].

Monoenergetic neutrons in the energy range from 5 to 9 MeV were obtained with the $D(d,n)He^3$ reaction using the Rice University 5.5 MeV Van de Graaff accelerator. The deuterium gas target had an entrance window of 0.65 mg/cm^2 or 0.77 mg/cm^2 nickel foil. The neutron energy resolution in the experiments was limited by the target thickness and the solid angle subtended by the sensitive volume of the ionization chamber. The energy resolution varied from 25 keV at 5.0 MeV to 50 keV at 8.5 MeV.

The ionization chamber was positioned so that the center of its sensitive volume was 40 cm from the neutron source and at 0° to the accelerator beam. The neutron flux was monitored with a long counter placed directly behind the ionization chamber and at one meter from the neutron source. The correction of the neutron flux monitored by the long counter to account for scattering and absorption of neutrons by the ionization chamber has been previously discussed[5)]

The pulses produced at the collection plate in the ionization chamber by disintegrations in the gas were amplified and then recorded with a 256-channel pulse height analyzer. The pulse height spectrum for a neutron energy of 7.22 MeV is shown in fig. 1. The ionization chamber was filled with 0.49 atmospheres of spectroscopic grade carbon dioxide and 1.22 atmospheres of commercial grade argon. The group of pulses in channel 137 corresponds to the (n, α_0) reaction in O^{16} leaving C^{13} in its ground state. This reaction has a Q-value of -2.20 MeV[6)]. The energy scale of the pulse height spectrum was calibrated using the Q-value of this reaction and of the $C^{12}(n, \alpha_0)Be^9$

reaction observed at higher neutron energies (fig. 2). In fig. 1 some evidence of the recoil spectra of O^{16} and C^{12} nuclei is seen in channels 47 and 59. The $O^{16}(n,\alpha_1)C^{13*}$ reaction leaving C^{13} in its first excited state is not observed at this neutron energy.

Also shown in fig. 1 is the spectrum of pulses due to the (n,α_o) reaction in O^{16} at a neutron energy of 6.79 MeV. At this energy the pulse group is double peaked and the pulse-height resolution is 15% as compared with 9% for the pulse spectrum at 7.22 MeV. The two shapes of these groups of pulses shown in fig. 1 are the limits of various shapes observed for this pulse group as the neutron energy was changed. This phenomenon is attributed to strong angular distribution effects in the $O^{16}(n,\alpha_o)C^{13}$ reaction since pulse groups corresponding to other reactions (in spectra observed at higher energies) maintain a normal shape with constant pulse-height resolution.

Pulses due to (n,α) reactions in A^{40}(Q= -2.49 MeV) are included in the group of pulses from the (n,α_o) reaction in O^{16}. A study of the neutron reactions in argon at this laboratory[7] has shown that the contribution from reactions in A^{40} is small below a neutron energy of 7.3 MeV. For measurements above this energy the ionization chamber was filled with a mixture of 0.12 atmospheres spectroscopic grade carbon dioxide and 1.48 atmospheres krypton. The pulse height spectrum obtained with this filling at a neutron energy of 8.09 MeV is shown in fig. 2. The pulse height resolution in this case is 7%. The groups of pulses in channels 181, 86, 68, and 63 correspond to (n,α) reactions in O^{16} leaving C^{13} in its ground, first, second, and third excited states respectively. The latter two groups of pulses are not resolved and are merged with the pulses due to recoils of C^{12} nuclei. In channel 74 a group of pulses is observed due to the (n, α_0) reaction in C^{12} leaving Be^9 in its ground state. This reaction has a Q-value of -5.70 MeV[6].

The rapidly rising tail in fig. 1 near channel 45 is mainly due to recoils of argon nuclei and to (n,p) reactions in the materials of the walls and plates of the ion chamber. The latter part of the tail, which extends to higher channels than that from the recoils of argon nuclei, was greatly reduced by covering the high voltage and the collection plates with 0.025 cm gold metal. The data in the present experiment above 7.3 MeV were obtained with the gold covered plates in the ionization chamber. Other background effects are due to particle tracks penetrating the boundary of the chamber sensitive volume and to reactions occurring in the gas between the grid and collection plates. These effects give a continuous distribution of pulses as seen in figs. 1 and 2.

3. Analysis of Data and Results

Excitation functions for the various reactions in oxygen and carbon were obtained by analyzing pulse-height distributions similar to those in figs. 1 and 2. The number of disintegrations associated with each particle group was determined by adding the counts in that group, subtracting the background, and correcting for the deadtime of the pulse height analyzer system and for wall loss. The wall loss for the ion chamber used in the present investigation has been measured previously for particles of various track lengths[4]. In the present experiment the wall loss for the alpha particles from the $O^{16}(n,\alpha_0)C^{13}$ reaction varied from 8% to 25%. For the alpha particles from the other reactions the loss was about 7%. The analyzer deadtime varied from about 1% to 10%.

The relative number of neutrons at each neutron energy was determined from the integrated deuteron beam current and the known cross section for the $D(d,n)He^3$ reaction[8] taking into account the variation of the neutron yield with angle of emission from the source. The relative neutron flux was also monitored with the long counter. Neutron backgrounds were measred by removing the deuterium gas from the target. After corrections for the background, for deadtime losses (4-25%) and for the efficiency of the counter relative to a Pu-Be neutron source using the data of Haddad et al.[9], the long counter monitor was in good agreement with the relative flux determined from the integrated beam current. The absolute neutron flux was obtained by comparison with a calibrated Pu-Be source placed one meter from the long counter. To obtain the average flux incident on the ion chamber an increase of 9% was made to account for attenuation by the chamber pressure vessel and a decrease of 2% to account for the variation of source intensity with angle.

Figures 3 and 4 show the cross sections for the (n,α) reactions observed in O^{16} and C^{12} as a function of the average neutron energy incident on the ion chamber. The absolute cross section for the $O^{16}(n,\alpha)C^{13}$ reaction at 5.05 MeV was found to be 147 mb and 153 mb in two separate experiments. The average value of these measurements is 150 ± 30 mb. In fig. 3 the cross section values above 7.1 MeV are the average of two separate experiments. The average absolute cross section at 7.20 MeV was calculated to be 213 ± 53 mb as compared to the value of 206 mb given in fig. 3 which is based on the absolute value at 5.05 MeV. The data shown in fig. 4 for the (n,α) reactions in O^{16} leaving C^{13} in excited states and for the (n,α) reaction in C^{12} are the result of a single experiment with the $Kr-CO_2$ gas mixture in the ionization chamber. The data for reactions in carbon were not analyzed for neutron energies below 7.88 MeV because of interference by the carbon nuclei recoils. The pulses from C^{12} recoils also caused a large uncertain background for the pulse group corresponding to the $(n, \alpha_2 + \alpha_3)$ reaction in O^{16}.

The major sources of error in the cross sections are (1) the determination of the absolute neutron flux from the long counter measurements, (2) counting statistics and adding the counts in each group of the pulse-height distribution, (3) background corrections, and (4) correction of each particle group for wall loss. Other sources of smaller errors have been previously discussed[5]. Determination of the neutron flux incident on the ion chamber in the manner outlined above should be accurate to ± 15%. The error from item (2) varied from ± 1% to ± 25%. As indicated in figs. 1 and 2 background corrections were negligible for the group corresponding to the (n,α_o) reaction in O^{16} but became increasingly important for lower energy groups. The resulting errors in the cross sections were estimated to be $\pm$ 2% and larger. The wall loss correction was estimated to cause errors up to about 4% in the cross sections.

Based on the above considerations, the excitation function for the (n, α_0) reaction in O^{16} is estimated to be in error from about $\pm$ 20% at 5 MeV to about $\pm$ 30% at 8.7 MeV. The error is considerably larger at neutron energies where the cross section becomes less than about 10 mb. Because of larger errors in background corrections and in adding counts in the groups, the cross sections for the (n, α_1) reaction in O^{16} and the (n, α_0) reaction in C^{12} have errors estimated to be $\pm$ 35%. It is difficult to determine the background error in the $(n, \alpha_2 + \alpha_3)$ reaction in O^{16} since little information is available about the angular distribution of neutrons elastically scattered from C^{12}. However, the cross section values for this reaction given in fig. 4 should be correct to about $\pm$ 50%.

Relative values of the cross sections in figs. 3 and 4 are more accurate than the absolute errors given in the discussion above.

The resonances observed in the excitation function for the $O^{16}(n, \alpha)C^{13}$ reaction are listed in Table 1. Also given in Table 1 are the experimental level widths in C^{13*} which were obtained from the observed resonance widths after correction for the neutron energy resolution and for center-of-mass energy.

4. Discussion

The cross section of 150 $\pm$ 30 mb measured at the 5.05 MeV resonance in the $O^{16}(n, \alpha_0)C^{13}$ reaction is in reasonable agreement with the value of 180 mb obtained by Walter, Clement and Boreli[2].

In the present experiment 21 resonances are observed in the excitation function for the $O^{16}(n,\alpha_o)C^{13}$ reaction (fig. 3) leaving C^{13} in its ground state. The neutron energies at which these resonances occur and the corresponding excitation energies in O^{17} are given in Table 1. Levels previously reported in O^{17} at 9.06 MeV[10] and at 9.78 MeV[11,12] corresponding to neutron energies in the $O^{16}(n,\alpha)C^{13}$ reaction of 5.22 MeV and 5.98 MeV respectively were not observed in the present experiment. The resonances observed below 6.5 MeV correspond to known levels in O^{17}, while with three exceptions the resonances observed above this energy correspond to unreported levels in O^{17} (based on the 1959 compilation of data by Ajzenberg-Selove and Lauritsen[13]). As indicated in Table 1 the existence of the resonances at 7.79 MeV and 8.06 MeV is not certain.

In addition to the resonances given in Table 1 a broad resonance structure centered at about 7.1 MeV may be possible as indicated by the dashed curve in fig. 3. The width of this broad structure is about 1.2 MeV as compared with the Wigner limit of about 10.6 MeV for s-wave neutrons and about 3.5 MeV for s-wave alpha particles at this excitation energy.

The excitation function for the $C^{12}(n,\alpha)Be^9$ reaction given in fig. 4 shows no definite resonance structure other than the broad maximum at about 8 MeV. The data for this reaction were averaged somewhat in order to smooth the excitation function. Over the energy range investigated in the present experiment the cross sections given in fig. 4 for this reaction should represent the total (n,α) reaction in C^{12} since the (n, α_1) reaction leaving Be^9 in its first excited state at 1.75 MeV is not possible below 7.9 MeV and would not contribute significantly until considerably higher neutron energies.

TABLE 1.

RESONANCES IN THE REACTION $O^{16}(n,\alpha)C^{13}$

RESONANCE	NEUTRON ENERGY (MeV)	EXCITATION IN O^{17} (MeV)	LEVEL WIDTH (keV)
A	5.05	8.89	~ 91
B	5.12	8.96	~ 30
C	5.32	9.15	~ 24
D	5.37	9.20	52
E	5.68	9.50	56
F	5.92	9.72	51
G	6.08	9.87	28
H	6.22	9.99	143
I	6.41	10.19	81
J	6.59	10.35 *	148
K	6.81	10.56	79
L	7.04	10.77 *	69
M	7.20	10.93	79
N	7.32	11.03 *	~ 57
O	7.59	11.29 *	~ 78
P	(7.79)	(11.48)*	..
Q	7.90	11.59	~ 126
R	(8.06)	(11.74)*	..
S	8.22	11.89 *	~ 125
T	8.38	12.04 *	~ 125
U	8.66	12.30 *	..

* Previously unreported.

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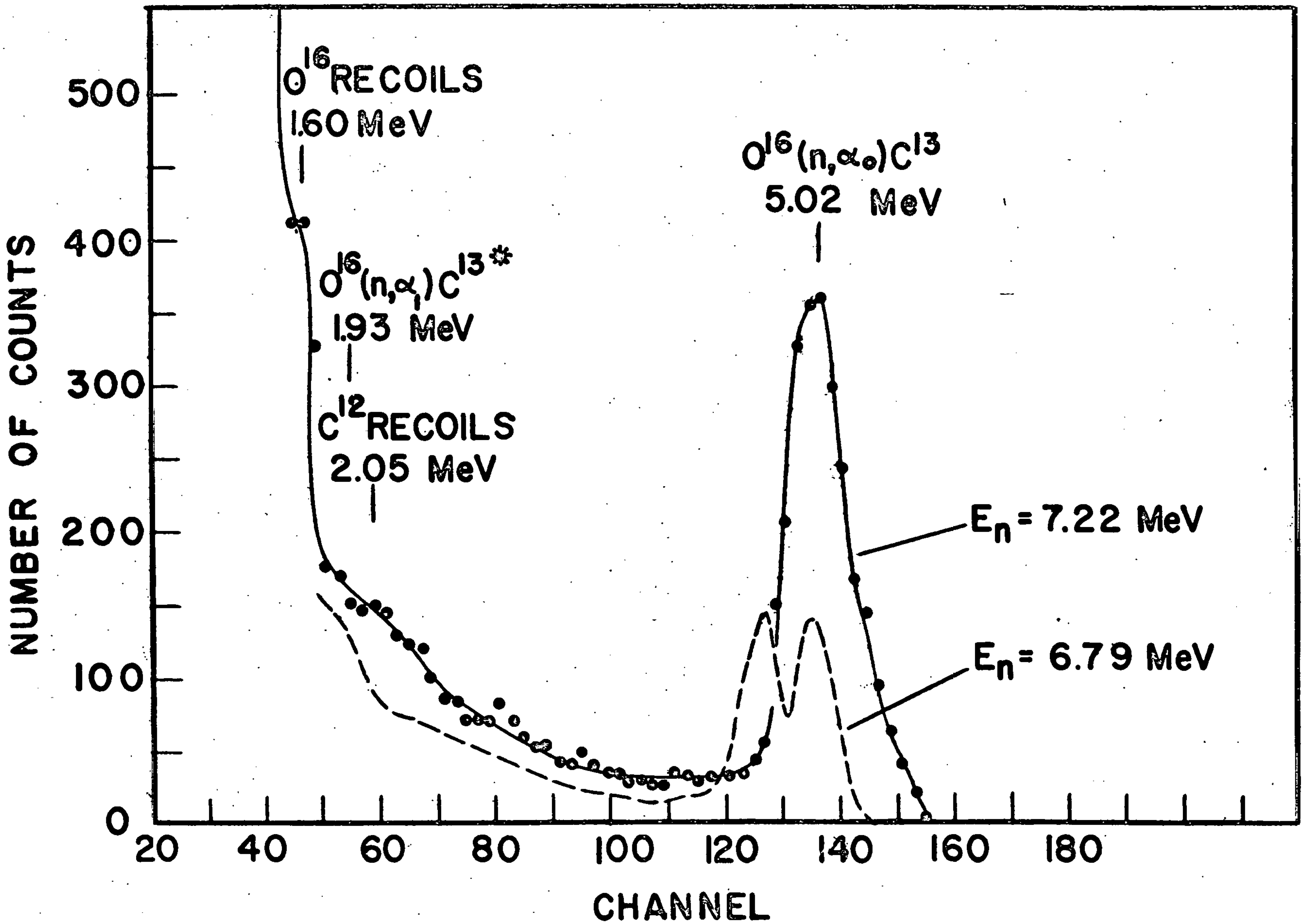
Figure Captions

Fig. 1 Pulse height distribution from disintegration of carbon dioxide by 7.22 MeV neutrons. The dashed curve is the distribution obtained with 6.79 MeV neutrons.

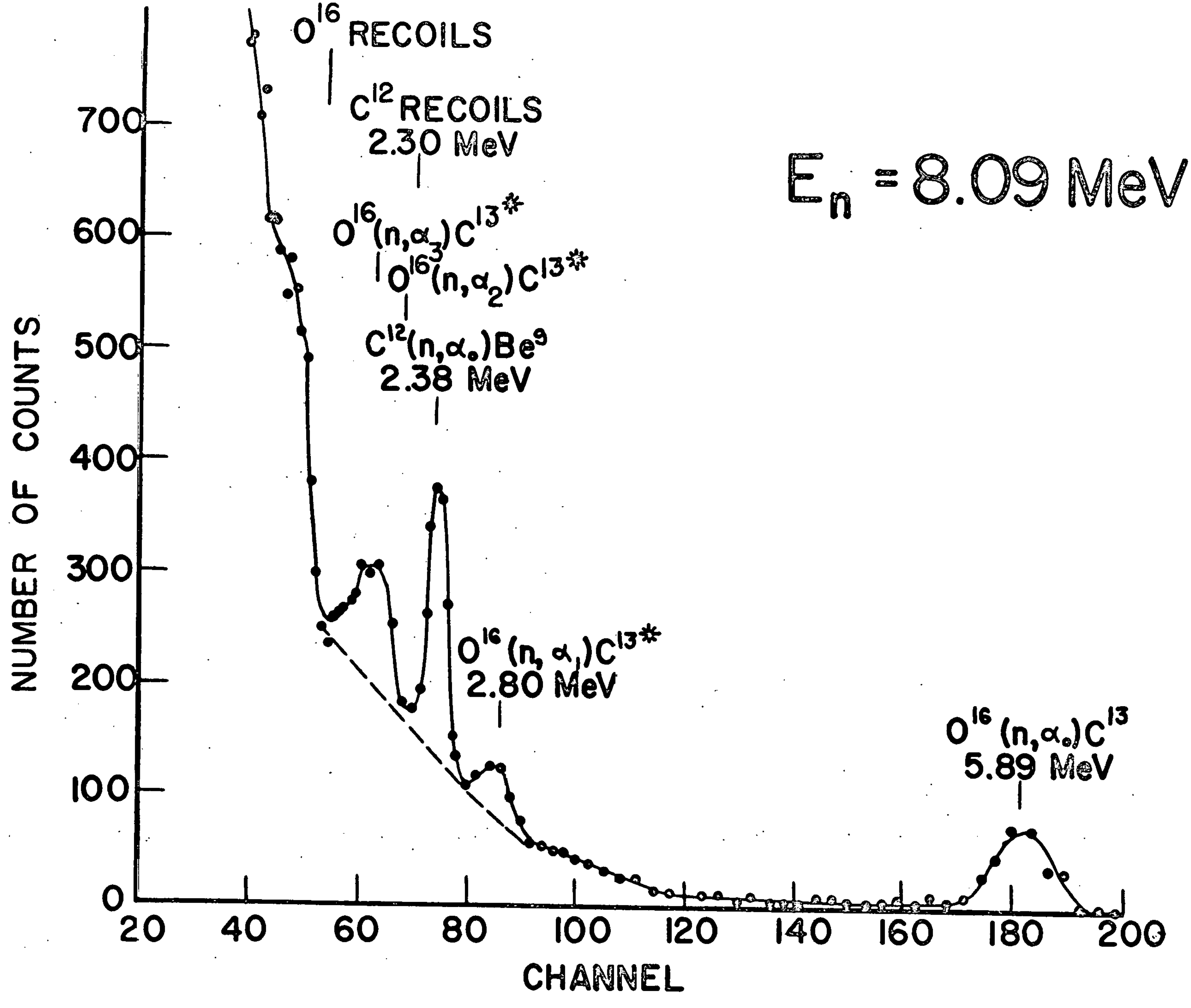
Fig. 2 Pulse height distribution from disintegration of carbon dioxide by 8.09 MeV neutrons. Dashed lines under groups indicate backgrounds to be subtracted.

Fig. 3 Cross section for the reaction $O^{16}(n, \alpha)C^{13}$ leaving C^{13} in its ground state. The dashed curve indicates possible broad resonance structure in the excitation function.

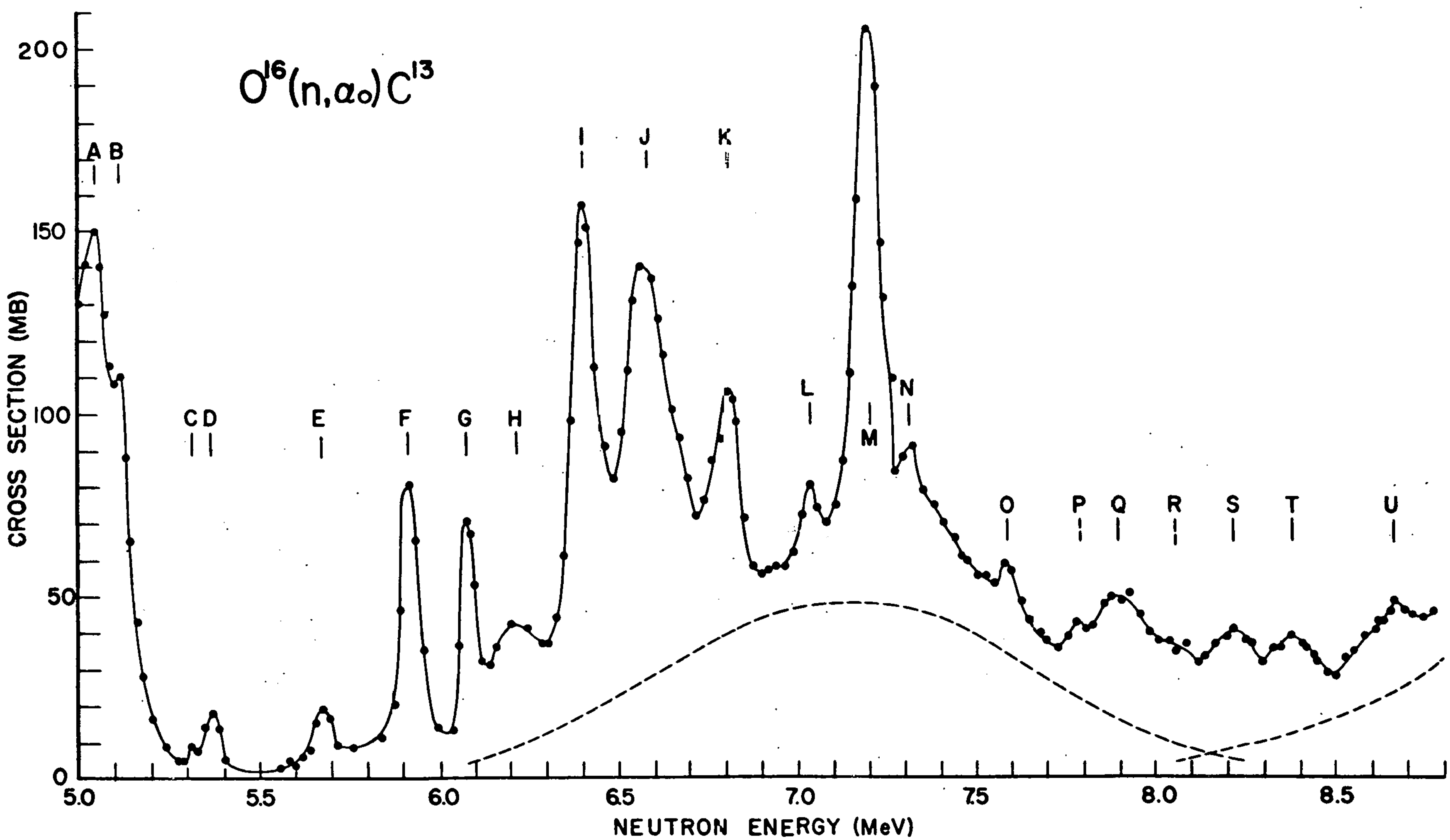
Fig. 4 Cross sections for (n, α) reactions in O^{16} and C^{12} obtained with neutron energies 7.5 to 8.7 MeV.



NUMBER OF COUNTS
CHANNEL
O^{16} RECOILS
1.60 MeV
$O^{16}(n,\alpha_1)C^{13*}$
1.93 MeV
C^{12} RECOILS
2.05 MeV
$O^{16}(n,\alpha_0)C^{13}$
5.02 MeV
E_n = 7.22 MeV
E_n = 6.79 MeV



O^{16} RECOILS
C^{12} RECOILS
2.30 MeV
$E_n = 8.09$ MeV
$O^{16}(n,\alpha_3)C^{13*}$
$O^{16}(n,\alpha_2)C^{13*}$
$C^{12}(n,\alpha_0)Be^9$
2.38 MeV
$O^{16}(n,\alpha_1)C^{13*}$
2.80 MeV
$O^{16}(n,\alpha_0)C^{13}$
5.89 MeV
NUMBER OF COUNTS
700
600
500
400
300
200
100
0
20
40
60
80
100
120
140
160
180
200
CHANNEL


$O^{16}(n,\alpha_0)C^{13}$
CROSS SECTION (MB)
NEUTRON ENERGY (MeV)
0
50
100
150
200
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
A
B
C
D
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G
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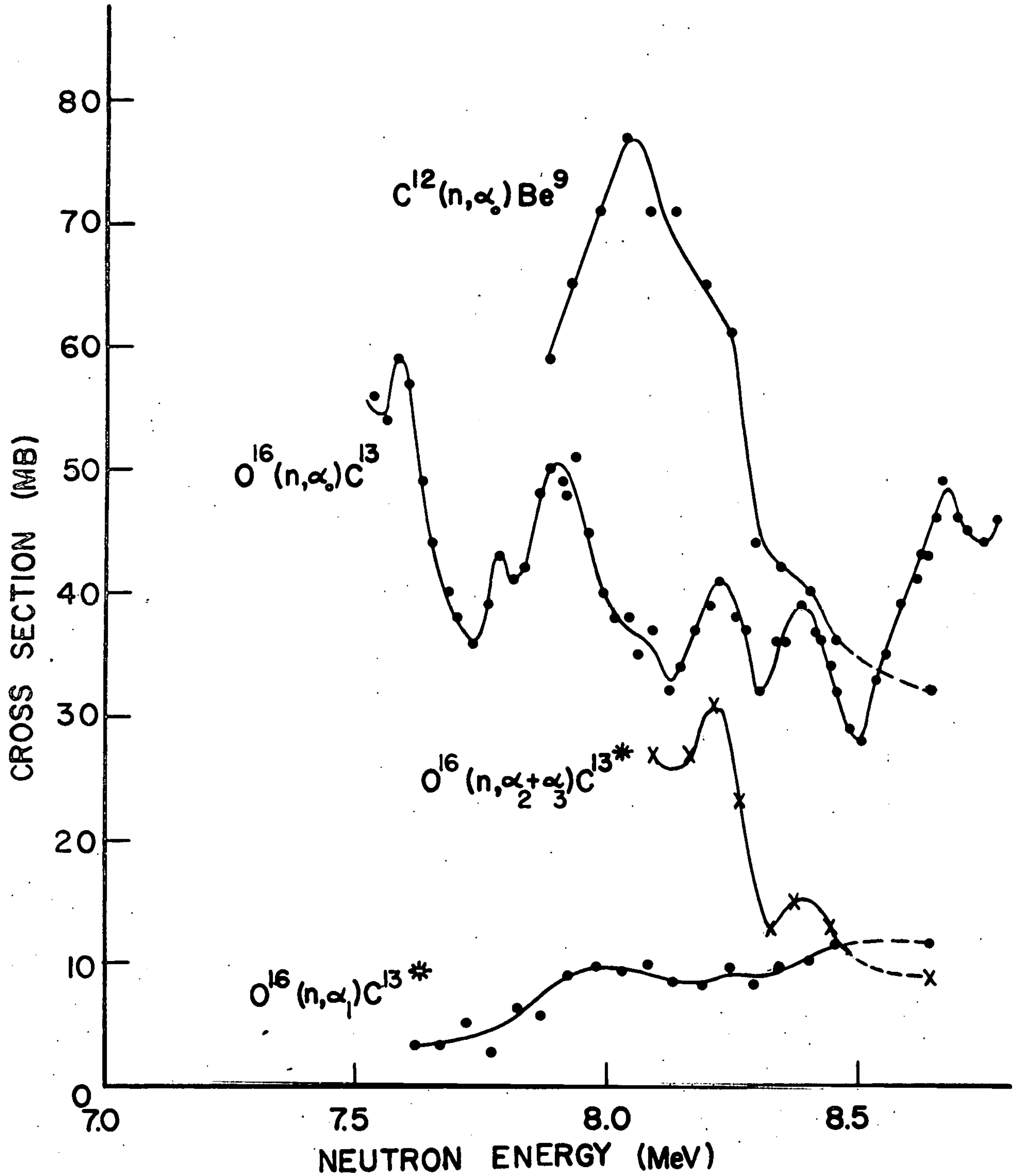
Q
R
S
T
U



CROSS SECTION (MB)
80
70
60
50
40
30
20
10
0
7.0
7.5
8.0
8.5
NEUTRON ENERGY (MeV)
C12(n,α0)Be9
O16(n,α0)C13
O16(n,α2+α3)C13*
O16(n,α1)C13*