Note added in proof. The single particle level splittings referred to above[12] were inadvertently multiplied by two before comparison with experiment. This disagreement is incidental to the main point of the paper, but it does weaken the conclusion pending a satisfactory calculation of the spin-orbit force. We thank H. A. Bethe and C. W. Wong for correspondence concerning this difficulty.

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$^{13}C(\alpha,n)^{16}O$ Reaction Cross Section between 1.95 and 5.57 MeV

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The $^{13}C(\alpha,n)^{16}O$ total cross section has been determined for the incident α-particle energy range 1.95 to 5.57 MeV using a 4π neutron detector. The total cross section of the inverse reaction $^{16}O(n,\alpha)^{13}C$ has been calculated by applying the reciprocity theorem. The total level widths for 16 levels, and the partial widths Γ_α and Γ_n along with the reduced widths γ_α^2 and γ_n^2 for the levels corresponding to the 2.68, 2.81, 3.72, and 4.62-MeV resonances, have been determined.

I. INTRODUCTION

THE measurement of the $^{13}C(\alpha,n)^{16}O$ reaction cross section is important for studying the level structure in the compound nucleus ^{17}O. The cross section in the range $E_\alpha=1.95$ to 5.57 MeV gives information about the levels in the excitation energy range of about 7.8 to 10.6 MeV. The elastic sacttering of α particles by ^{13}C, neutrons by ^{16}O, and the radiative capture of α particles by ^{13}C are other possible reactions leading to this range of excitation energies in ^{17}O. No direct measurements of the total $^{13}C(\alpha,n)^{16}O$ reaction cross sections are available, whereas there are many previous measurements of the differential cross sections of this reaction. Becker and Barschall[1] and Walton *et al.*[2] have measured the differential cross sections for the incident α-particle energy range 2–3.5 MeV and Bonner *et al.*[3] for the energy range 2–5 MeV. Barnes *et al.*[4] have measured the $^{13}C(\alpha,\alpha)^{13}C$ differential cross section from $E_\alpha=2$ to 3.5 MeV. A useful aspect of the total-cross-section measurement of $^{13}C(\alpha,n)^{16}O$ reaction is the calculation of the total cross section for the inverse reaction, $^{16}O(n,\alpha)^{13}C$, using reciprocity. The $^{16}O(n,\alpha)^{13}C$ reaction cross sections are useful for reactor calculations. Direct measurements of this cross section have been made by Seitz and Huber,[5] Davis *et al.*,[6] and Lister and Sayres.[7] From the $^{13}C(\alpha,n)^{16}O$ differential cross-section values, Walton *et al.*[2] have obtained the total (α,n) cross section for this reaction up to 3.5 MeV. A direct measurement of this reaction cross section has been done at Trombay for the incident α-particle energy range 1.95–5.57 MeV using a 4π geometry neutron detector.

II. EXPERIMENTAL METHOD

Singly ionized helium ions from the 5.5-MeV HVEC Van de Graaff Accelerator at Trombay[8] were used to bombard an electromagnetically enriched (enrichment $\approx 30\%$) ^{13}C target[9] deposited on a 0.25-mm-thick tantalum backing. The neutrons were detected by a calibrated 4π detector built according to the design of Marion *et al.*,[10] the ^{13}C target being mounted at the center of the counter. The counter consists of an inner and outer set of BF_3 counters embedded in a block of paraffin. The efficiency of this counter, as a function of the neutron energy, was obtained from the measurement of the neutron yields from the $^7Li(p,n)^7Be$ reaction.[11] The cross section of this reaction has been determined by Gibbons and Macklin.[12] The efficiency curve was extended up to 5-MeV neutron energy by using a 50-millicurie Ra-α-Be neutron source. The efficiency curves are shown in Fig. 1.

The number of ^{13}C nuclei per square centimeter present in the carbon target was determined by measuring the neutron yield at 3.5 and 4.1 MeV from the $^{13}C(p,n)^{13}N$ reaction using the same neutron counter and comparing the results with the previous cross-section measurements of Gibbons and Macklin.[12] From the ex-

[1] R. L. Becker and H. H. Barschall, Phys. Rev. **102**, 1384 (1956).
[2] R. B. Walton, J. D. Clement, and F. Boreli, Phys. Rev. **107**, 1065 (1957).
[3] T. W. Bonner, Alfred A. Kraus, Jr., J. B. Marion, and J. P. Schiffer, Phys. Rev. **102**, 1348 (1956).
[4] B. K. Barnes, T. A. Belote, and J. R. Risser, Phys. Rev. **140**, B616 (1965).
[5] J. Seitz and P. Huber, Helv. Phys. Acta **28**, 227 (1955).
[6] E. A. Davis, T. W. Bonner, D. W. Worley, Jr., and R. Base, Nucl. Phys., **48**, 169 (1963).
[7] D. Lister and A. Sayres, Phys. Rev. **143**, 745 (1966).
[8] A. S. Divatia *et al.*, Atomic Energy Establishment Trombay Report No. AEET/NP/5, 1962 (unpublished).
[9] Supplied by the Electromagnetic Separation Group, Atomic Energy Research Establishment, Harwell, England.
[10] J. B. Marion, R. J. A. Levesque, C. A. Ludemann, and R. W. Detenbeck, Nucl. Instr. Methods **8**, 297 (1960).
[11] K. K. Sekharan, M.Sc. thesis, University of Bombay, 1965 (unpublished).
[12] J. H. Gibbons and R. L. Macklin, Phys. Rev. **114**, 571 (1959).

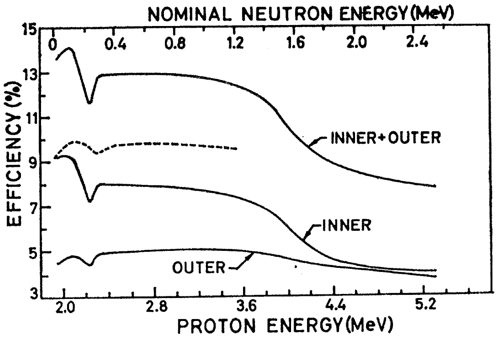

FIG. 1. The efficiency of the 4π neutron counter as a function of the nominal neutron energy (energy of neutrons emitted at 90° with respect to the incident beam of protons). The efficiency of the inner and the outer set of counters as well as the sum of the efficiencies of these two sets are shown by separate curves. The estimated error in the determination of the absolute efficiency is $\pm 12\%$. The dashed line shows the total efficiency of the 4π counter designed by Marion *et al.* (Ref. 10).

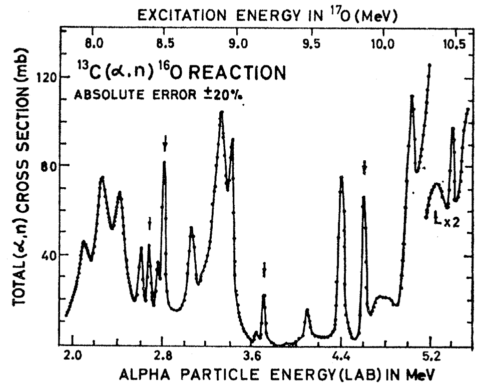

FIG. 2. The total (α,n) cross section in millibarns for the $^{13}C(\alpha,n)^{16}O$ reaction as a function of the incident alpha-particle energy in MeV (laboratory system). The absolute error in the cross-section values is estimated to be $\pm 20\%$. The excitation energy in ^{17}O is indicated on the top horizontal axis. For the resonances indicated by arrows the partial widths and reduced widths have been obtained.

perimental half-width of very narrow resonances in the $^{13}C(\alpha,n)^{16}O$ reaction the total target thickness (^{12}C and ^{13}C) was estimated to be 31 keV for 3.1-MeV alpha particles. The details of the accelerator calibration have been reported previously.[13] The relative error in the incident α-particle energy is estimated to be ± 3 keV. The incident beam was monitored by a current integrator[14] built at Trombay, following a design given by Smulders and Smith.[15] The integration was accurate to $\pm 2\%$.

III. EXPERIMENTAL RESULTS

The neutron yield was measured for the incident α-particle energy range 1.95–5.57 MeV in steps varying from 6–8 keV. The background was determined by measuring the yield of neutrons when the beam was incident on the tantalum backing. It was possible to turn the target through 180° without breaking the vacuum. The background was found to be a negligibly small percentage of the total yield, except at energies in the neighborhood of $E_\alpha = 4$ MeV, where the cross section is very low. The total (α,n) cross section is shown in Fig. 2 as a function of the incident α-particle energy.

The factors contributing to the error in the cross section are the determination of the counter efficiency, the number of ^{13}C nuclei, and the error in current integration. The error in the counter efficiency values is estimated to be $\pm 12\%$; the cross section is estimated to be accurate to $\pm 20\%$.

There are about 20 resonances corresponding to the levels in ^{17}O in the excitation energy range 7.8–10.6 MeV. The resonance-energy values listed in Table I are the energies halfway through the target thickness. The excitation energy values and the peak (α,n) cross section values are also given in Table I. The resonance at 4.49 MeV is not separated from the strong resonance at 4.42 MeV. The broad resonance reported by Bonner *et al.*[3] at 4.77 MeV is found to consist of two overlapping resonances with peaks at 4.77 and 4.85 MeV.

By applying the reciprocity theorem, the cross section for the inverse reaction $^{16}O(n,\alpha)^{13}C$ was calculated up to incident α-particle energy 5.05 MeV. This is the threshold energy for the first excited state group and it is not possible to obtain the inverse reaction cross section beyond this energy. The peak (n,α) cross section values[16] and the neutron energies corresponding to the resonance energies of the alpha particles are tabulated in Table I. A comparison of the peak cross-section values with those reported by Davis *et al.*,[6] Walton, Clement, and Boreli,[2] and Lister and Sayres shows good agreement for most of the resonances. The (n,α) cross sections are shown in Fig. 3.

IV. ANALYSIS

The excitation function shows narrow isolated resonances as well as some broad overlapping resonances. These resonances were grouped into two categories: (a) those which are very narrow compared to the thickness of the target in terms of alpha particle energy loss, and (b) those which are wider than or nearly as wide as the target.

The total widths Γ of those levels belonging to category (a) were determined by Richard's leading-edge method.[17] For the wide resonances, Γ was obtained di-

[13] M. K. Mehta, Joseph John, S. S. Kerekatte, and A. S. Divatia Nucl. Phys. **89**, 22 (1966); M. K. Mehta, Joseph John, S. S. Kerekatte, and A. S. Divatia, Atomic Energy Establishment Trombay Report No. AEET-258, 1966 (unpublished), p. 4.

[14] A. S. Divatia, Atomic Energy Establishment Trombay Report No. AEET/NP/8, 1964 (unpublished), p. 12.

[15] P. J. M. Smulders and P. B. Smith, Nucl. Instr. Methods **8**, 40 (1960).

[16] A. S. Divatia, K. K. Sekharan, and M. K. Mehta, in Proceedings of the Conference on Nuclear Data, Microscopic Cross Sections, and Other Data Basic for Reactors, Paris, 1966 (to be published).

[17] H. T. Richards, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part A, Chap. I.D., p. 128.

TABLE I. Peak total cross sections and total widths of levels in ^{17}O.

Resonance energy E_α (MeV)	Excitation energy in ^{17}O E_x (MeV)	Peak total cross sections $^{13}C(\alpha,n)^{16}O$ (mb)	$^{16}O(n,\alpha)^{13}C$ (mb)	Neutron energy E_n (MeV)	Total level width (c.m.) Γ (keV)
2.08	7.94	46.4	63	4.05	$79^b\pm10$
2.25	8.07	75.0	107	4.18	$71^b\pm8$
2.41	8.19	68.7	102	4.32	$71^b\pm5$
2.61	8.34	43.6	67	4.47	$9^a\pm3$
2.68	8.40	45.2	71	4.53	$4^a\pm3$
2.77	8.47	37.9	60	4.60	$7^a\pm3$
2.81	8.50	82.0	132	4.64	$5^a\pm3$
3.07	8.69	52.7	88	4.84	$50^b\pm3$
3.32	8.89	105.2	183	5.05	$101^b\pm3$
3.42	8.96	93.1	164	5.13	$21^b\pm3$
3.65	9.14	6.7	12	5.32	$4^a\pm3$
3.72	9.19	23.5	43	5.38	$4^a\pm3$
4.12	9.50	17.3	33	5.71	$8^a\pm3$
4.42	9.73	75.6	149	5.91	$15^a\pm3$
(4.49)	(9.78)	...	...	...	...
4.62	9.88	67.0	134	6.11	$5^a\pm3$
(4.77)	(9.99)	(23.2)	47	6.23	...
(4.85)	(10.05)	(22.9)	47	6.29	...
5.04	10.20	113.1	...	...	$50^b\pm3$
5.29	10.39	147.7	...	...	...
5.41	10.49	197.4	...	...	...

[a] Determined by the leading-edge method of Richards.
[b] Determined directly as explained in the text.

TABLE II. The partial widths and reduced widths for levels in ^{17}O.

Resonance energy, E_α (MeV)	J^a	l_α	Γ_α (keV)	γ_α^2 (keV)	l_n	Γ_n (keV)	γ_n^2 (keV)	Percentage of Wigner limit θ_α	θ_n
2.68	$\frac{5}{2}+$	3	0.16	2.3	2	3.84	1.6	0.365	0.058
2.81	$\frac{5}{2}-$	2	0.43	1.3	3	4.57	5.0	0.206	0.182
3.72	$\frac{5}{2}$	2	0.14	0.11	3	3.86	3.1	0.017	0.113
		3		0.31	2		1.3	0.049	0.047
4.62	$\frac{9}{2}$	4	0.30	0.82	5	4.70	100	0.130	3.635
		5		4.57	4		12	0.725	0.436

[a] Values of J were taken from Ref 4.

rectly from the experimental width Γ_{exp} and the target thickness T, since $\Gamma_{exp}^2=\Gamma^2+T^2$. The spread in the incident-beam energy was negligibly small. In evaluating the level width, the determination of the off-resonance value of the cross section was a major problem. The error in the width is estimated for each resonance separately. Since the data were taken in 6-keV steps, the minimum error estimated was ±3 keV.

The partial widths of four resonances at $E_\alpha=2.68$, 2.81, 3.72, and 4.62 MeV have been calculated using the relationship given by Gove,[18]

$$\frac{2\epsilon}{\lambda^2}y(\infty,\infty)=\frac{(2J+1)}{(2I+1)(2i+1)}\sum\frac{\Gamma_\alpha\Gamma_n}{\Gamma}, \qquad (1)$$

where ϵ is the stopping power of the target in units of energy times cm^2/atom; λ is the center-of-mass wavelength of the incident particle in centimeters; $y(\infty,\infty)$ is the step in the thick-target yield in units of reactions

[18] H. E. Gove, in *Nuclear Reactions*, edited by P. M. Endt and M. Demeur (Interscience Publishers, Inc., New York, 1959), Vol. 1, Chap. 6, p. 302.

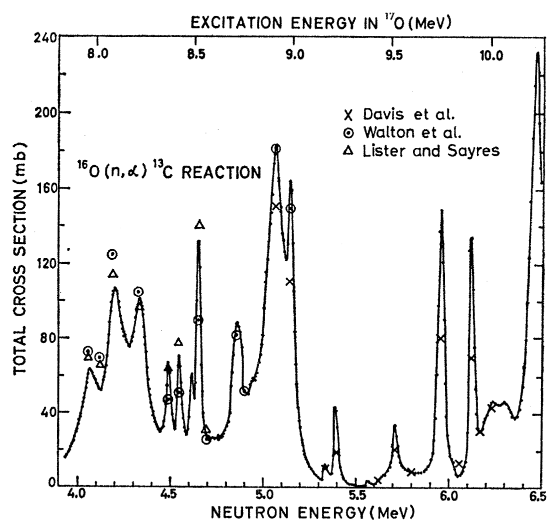

FIG. 3. The excitation function for the $^{16}O(n,\alpha)^{13}C$ reaction obtained by applying the reciprocity theorem. Some of the $^{16}O(n,\alpha)^{13}C$ cross-section values obtained by direct measurement by Davis *et al.* (Ref. 6), Walton, Clement, and Boreli (Ref. 2), and Lister and Sayres (Ref. 7) are shown for comparison.

per incident particle; J is the total angular momentum of the compound nucleus level; i,I are the spin angular momenta of the incident and the target nucleus, respectively; and Γ, Γ_α, and Γ_n are the total width, the partial alpha width, and partial neutron width, respectively.

This expression could be used to evaluate the products of partial widths Γ_α and Γ_n of these four levels since the target thickness in terms of the α-particle energy loss was more than five times the natural widths of these levels. The values of Γ_α and Γ_n were obtained assuming $\Gamma_\alpha+\Gamma_n=\Gamma$ and neglecting Γ_γ ,since there are no other channels open. It is also assumed that $\Gamma_n>\Gamma_\alpha$. In view of the Coulomb barrier for the α particles, this is a reasonable assumption; however, it may not be valid in all cases. The reduced width and the ratio of the reduced width to the Wigner limit, as a percentage, were calculated from the expressions

$$\Gamma_s=2P_l\gamma_s^2\,, \qquad (2)$$

$$\theta_s=100\gamma_s^2/(3\hbar^2/2m_sa_s^2)\,, \qquad (3)$$

where P_l is the penetrability factor for the lth partial wave, γ_s^2 is the reduced width of the level for the channel s, θ_s is the reduced width in terms of the Wigner limit, expressed as a percentage, and m_s and a_s are the reduced mass and the channel radius, respectively. The radii for the α channel and the neutron channel were taken as 5.7×10^{-13} cm and 4.9×10^{-13} cm, respectively. The α penetrabilities were taken from the table by Sharp *et al.*[19] and neutron penetrabilities from *Nuclear Data Tables*[20] and the tables of neutron penetrabilities and shift functions by Monahan *et al.*[21]

The reduced widths for some of the levels in ^{17}O have been reported previously.[2,4,7] Lister and Sayres[7] have estimated γ_n^2 for 5 levels in the excitation-energy range 7.24–8.07 MeV, by the elastic scattering of neutrons by ^{16}O. Barnes *et al.*[4] have obtained reduced widths in terms of the Wigner limit, from fits to the differential elastic scattering cross section of the $^{13}C(\alpha,\alpha)^{13}C$ reaction and the differential cross section of the $^{13}C(\alpha,n)^{16}O$ reaction at zero degrees. This is in the excitation-energy range 7.9–8.9 MeV. The present work provides reduced widths for some levels in the excitation-energy range up to 10 MeV. θ_α and θ_n obtained in the present work for resonances at $E_\alpha=2.68$ and 2.81 MeV are smaller by a factor of 3 than the values of Barnes *et al.*[4]

[19] W. T. Sharp, H. E. Gove, and E. B. Paul, *Graphs of Coulomb Functions TPI 70* (Atomic Energy of Canada Ltd., 1960).

[20] J. B. Marion, *Nuclear Data Tables* (National Academy of Sciences–National Research Council, Washington, D. C., 1960), Part 3, p. 94.

[21] J. E. Monahan, L. C. Biedenharn, and J. R. Schiffer, Argonne National Laboratory Report No. ANL5846 (unpublished).

V. CONCLUSIONS

The total (α,n) cross section for the $^{13}C(\alpha,n)^{16}O$ reaction has been measured in the bombarding-energy range from 1.95–5.57 MeV with an accuracy of $\pm20\%$. The cross section for the inverse reaction $^{16}O(n,\alpha)^{13}C$ has been calculated by applying the reciprocity theorem. The total widths Γ for 16 levels in the compound nucleus ^{17}O have been determined. The partial widths Γ_α and Γ_n and the corresponding reduced widths γ_α^2 and γ_n^2 have been calculated for four levels, the spins of which are known. Because of the assumptions made in evaluating the partial widths, Γ_α is always smaller than Γ_n. But it is possible that Γ_α is greater than Γ_n in some cases. This can be ascertained only if the $^{13}C(\alpha,\alpha)^{13}C$ cross sections are also measured for these levels. For example, Risser[22] has obtained a larger Γ_α than Γ_n for the resonance at 3.73 MeV. A knowledge of the total (α,n) cross sections as measured in this work as well as the elastic scattering cross sections will facilitate the determination of the spin and parity of the observed resonances.

ACKNOWLEDGMENTS

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[22] J. R. Risser (private communication).