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Investigation of States in ^{17}O via Neutron-Polarization Measurements in the ^{13}C(α, n) ^{16}O Reaction[*]

W. L. Baker,[†] C. E. Busch,[‡] J. A. Keane, and T. R. Donoghue
Department of Physics, The Ohio State University, Columbus, Ohio 43210

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Neutron-polarization angular distributions have been measured at six α-particle energies between 3.36 and 4.80 MeV for the ^{13}C(α, n_0)^{16}O reaction in order to investigate the level structure of ^{17}O between 8.7 and 10.2 MeV. These measurements have been analyzed together with the previous cross-section data of Walton, Clement, and Boreli and Kerr, Morris, and Risser using an S-matrix search code to yield a number of J^π assignments to ^{17}O levels in this energy interval. Although most assignments agreed with previous results, the assignment for the 9.95-MeV state must be changed to $\frac{5}{2}^+$. The existence of broad states near 8.7 and 9.6 MeV have been confirmed and assigned J^π values of $\frac{1}{2}^-$ and $\frac{3}{2}^-$, respectively.

I. INTRODUCTION

The excitation curves reported by many authors[1-7] for the ^{13}C(α, n)^{16}O reaction exhibit considerable structure for the α-particle energy range up to 10 MeV, indicating that the reaction proceeds preferentially via formation of states in the ^{17}O compound nucleus. Below $E_\alpha = 5$ MeV, sharp structure is superimposed on a few broad states, all of which appear to be identifiable. This structure changes dramatically above 5 MeV, as the number of contributing levels increases significantly, and overlapping of the levels is so great that the identification of individual resonances becomes difficult. Because this reaction provides insight into the level structure of ^{17}O at energies where little is known, several analyses[1-5] of this reaction have been reported to make J^π assignments to the contributing states. The reaction is a particularly simple case to analyze. As the entrance- and exit-channel spins are $\frac{1}{2}$ and the ground-state J^π's of ^{13}C and ^{16}O are $\frac{1}{2}^-$ and 0^+, respectively, a state in ^{17}O of definite J^π may be formed by only a single value l. The respective angular momenta are related by $l' = l \pm 1$. The J values for the contributing states can be determined from an analysis of the angular distributions, but the parity of the state often remains in question. This arises because the angular distribution remains unchanged when l and l' are interchanged.[3] When several states overlap, however, the relative parities of the states can usually be determined.[1] Additional experimental information must clearly be provided if firm assignments are to be deduced.

Most of the analyses[1-3,5,6] of the (α, n) reaction have been carried out for $E_\alpha < 5$ MeV, and, to avoid the parity ambiguity cited above, have generally included some (α, α) scattering results, or, in the case of Walton, Clement, and Boreli (WCB)[3] measurements from the ^{16}O(n, α) reaction and the total cross section of neutrons on ^{16}O. Although the latter authors were able to make firm J-value assignments for resonances up to $E_\alpha = 3.5$ MeV, expected ambiguities in the parity assignments for some of the states were noted. Kerr, Morris, and Risser (KMR)[2] recently investigated the 3.5- to 6.5-MeV region via measurements for the (α, n) and (α, α) interactions. An analysis of their (α, n) data was carried out using the simple single-level approximation, and therefore did not take coherent mixing of the overlapping states into proper consideration. These authors also took into consideration (α, α) excitation-curve data measured at those backward angles where the peaks due to α-particle scattering from ^{12}C and ^{13}C could be resolved. A number of J^π assignments were made for resonances below $E_\alpha = 5$ MeV in this work, but considerable difficulty in analyzing the structure above this energy was encountered. The recent measurements and elaborate analysis carried out by Robb, Schier, and Sheldon (RSS)[4] for $E_\alpha = 5$ to 8.66 MeV met with more success in this difficult energy range. As the analysis of KMR[2] might be too simplified even for the complexity of the structure observed below 5 MeV, some of the assignments made could be in error. A reinvestigation of the level structure for $E_\alpha = 5$ MeV therefore seemed worthwhile, particularly if additional experimental evidence could be included in the analysis, to provide an independent check on their assignments.

For this purpose, the polarization of the neutrons in the ^{13}C(α, n) reaction has been measured because this quantity is generally known to be sensitive to the character of the contributing states. The measurements were made for the α-particle energy region between 3.36 and 4.80 MeV to investigate states in ^{17}O between 8.7 and 10.2 MeV. As some of the resonances in this region are very pronounced and narrow, thin targets are required for a proper investigation. Fortunately, the reaction cross section is large enough (2 to 80 mb/

sr), that double-scattering experiments are feasible. The measurements reported here consist of several polarization excitation curves, and six polarization angular distributions, each measured close to a resonance energy. These data have been analyzed together with the previous cross-section data of WCB[3] and of KMR[2] using an S-matrix search code. Schölermann[8] recently reported polarization measurements in the 1.38- to 2.26-MeV energy range made using a thick (~1 MeV) target and also an analysis similar to that of the present work. Because some of the assignments made by Schölermann differed from those based on n-^{16}O scattering studies, Donoghue *et al.*[9] remeasured the polarizations using a thin target (~80 keV), as discussed elsewhere. A discussion of the experimental techniques employed, the experimental results, and the analysis are presented below.

II. EXPERIMENTAL METHOD

The polarization of the neutrons was determined by measuring the asymmetry in the scattering of the neutrons from helium using the apparatus illustrated schematically in Fig. 1. A detailed description of the polarimeter is given by DeMartini, Soltesz, and Donoghue[10] with subsequent modifications noted below.

Briefly, the neutrons emitted in the reaction at an angle θ_1 traverse the axis of a solenoid which is used to rotate the polarization vector of the neutron beam through $\pm\pi/2$, a technique[11] that interchanges the roles of the two neutron detectors without any physical exchange being made. The neutrons scattered through 121° (lab) from a high-pressure helium gas scintillator (180-atm He, 20-atm Xe) are detected by either of two $3\times2\times6$-in. Pilot-B plastic neutron detectors. A fast coincidence ($2\tau = 10$ nsec) is then required between the helium scintillator and either of the two neutron detectors, using the electronics configuration shown in Fig. 2. The fast-coincidence signal is used to gate a Northern Scientific analog-to-digital converter (ADC), whose linear input is a signal from the helium scintillator. The ADC is used in conjunction with an IBM 1800 on-line computer where the pulse-height spectra are stored. The fast-coincidence signal was also used to route the pulse-height spectra into one of four different portions of the computer core, depending on whether the neutrons were scattered into the top or bottom neutrons detector and on whether the neutron-spin precession was through $+\pi/2$ or $-\pi/2$. The electronics arrangement also permitted a simultaneous measurement of the accidental-coincidence spectra by delaying the fast signal from the helium scintillator by 70 nsec. The latter events were stored in a separate portion of core, as indicated in Fig. 2, and were used to correct the foreground spectra in the determination of the asymmetry. A typical gated helium recoil spectrum is shown in Fig. 3, showing the good separation of the ground-state neutron group.

The asymmetry P_1P_2 is calculated by summing the counts in the gated recoil peaks in each of the four spectra and combining them in a geometric

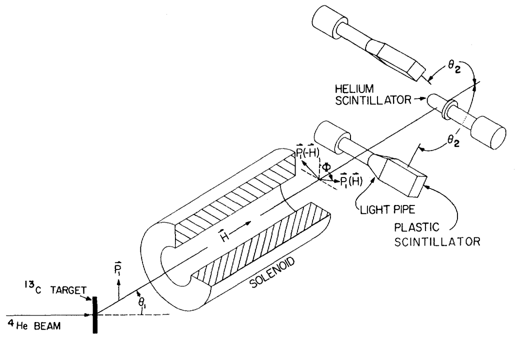

FIG. 1. Schematic drawing of the neutron polarimeter.

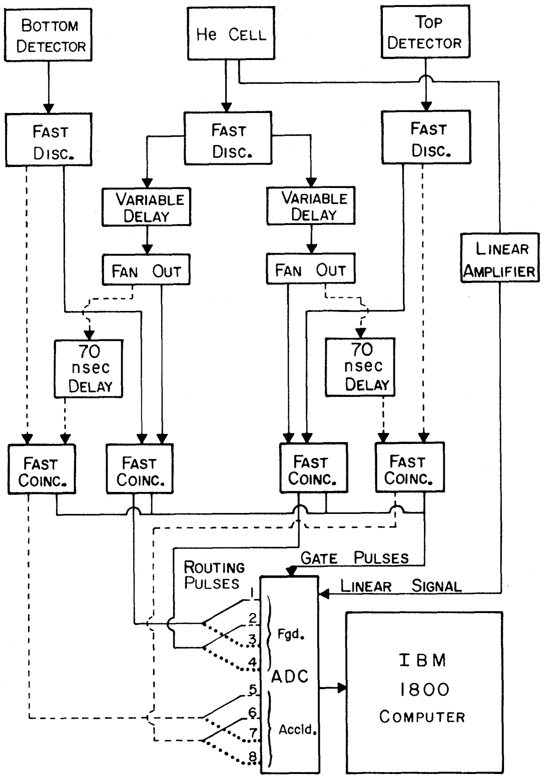

FIG. 2. Schematic of the fast electronics used and the interface of this to the IBM 1800 computer used for om-line data acquisition and data reduction. The dashed lines indicate the arrangement used for measuring accidental-coincidence counts simultaneously.

manner[12] so as to eliminate instrumental asymmetries. The analyzing power P_2, calculated from the recent n-α phase shifts of Morgan and Walter,[13] is averaged over the finite geometry of the helium scintillator and the neutron detectors via a computer program,[14] thereby permitting a determination of P_1. Corrections to the pulse-height spectra were made for background counts arising from accidental coincidences (0.5% contribution) and true coincidences due to indirect neutrons from the target (2% contribution). A small correction to the asymmetry was also made in several of the measurements for incomplete precession of the neutron spins. All of the above corrections to the data were made on line via the computer. Towards the latter stages of these measurements, the computer assumed full control over the routine details of the experimental data-gathering procedures, such as automatic reversal of the magnetic field in the presession solenoid in a prescribed sequence, the reading of monitor scalers and outputting this information on a line printer, making all corrections to the data outlined above, and, of greater importance, the periodic calculation of the reaction polarization and its uncertainty. With this system, the efficiency and accuracy with which polarization measurements can be made is greatly increased, and numerous consistency checks can be made on the data while it is being accumulated, which is of great advantage when each data point requires many hours of beam time.

As pointed out above, the resonances in this reaction in the energy range of interest are generally narrow and their study requires the use of thin uniform targets. These targets were made by cracking methyl iodide (55% enriched in ^{13}C) onto hot 0.005-in.-thick tantalum disks. The target thicknesses, determined by measuring the yield of the $^{13}C(p,\gamma)^{14}N$ reaction over the narrow ($\Gamma = 75$ eV) resonance at $E_p = 1.75$ MeV, ranged 20 to 80 $\mu g/cm^2$, corresponding to energy thicknesses of 25–100 keV for 4.5-MeV α particles. In the measurements, the targets used always had thicknesses less than the width of the resonance under investigation, except for the very narrow resonance at 4.58 MeV ($\Gamma = 15$ keV) where yield considerations precluded the use of a thinner target.

As many of the polarization angular distributions were measured at the peak energies of the narrow resonances, any appreciable carbon buildup on the targets during the long measuring times required to obtain good statistics (i.e., 4 to 12 h per data point) would shift the mean α-particle energy off resonance. Consequently much effort was devoted to minimizing and to monitoring this buildup. The target chambers were kept clean, and a liquid-nitrogen trap was installed in the beam line near the target. Each angular distribution was measured with (at least) one fresh ^{13}C target. The neutron flux was continuously monitored with the helium scintillator to detect any changes in reaction yield

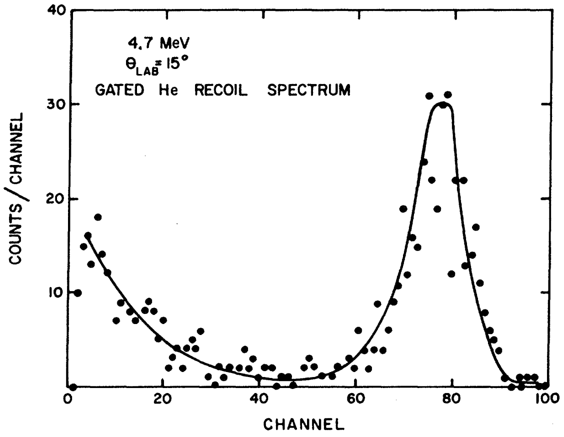

FIG. 3. A gated n-α recoil spectrum illustrating the relatively clean separation of the ground-state neutron group from the background.

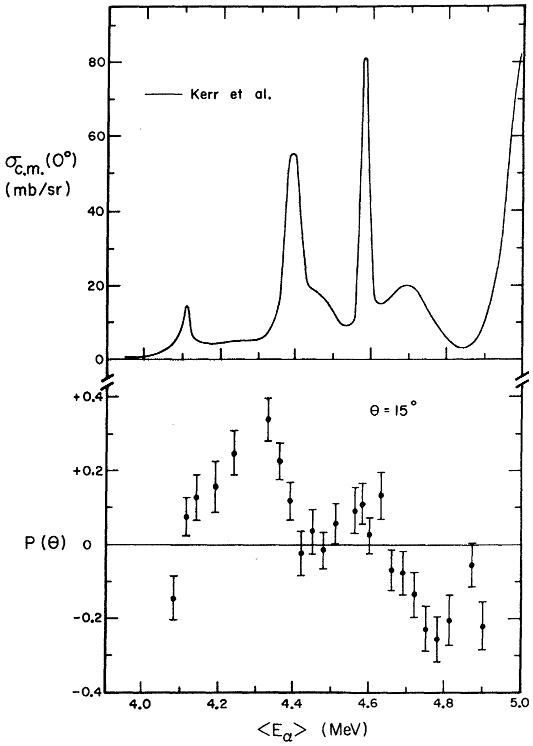

FIG. 4. A 0° cross-section excitation curve reported by KMR for a portion of the energy region explored in the present work. A polarization excitation curve measured at 15° shows much structure but no outstanding correlation is discernible between $\sigma(\theta)$ and $P(\theta)$.

due to energy shifts. In addition, cross-section excitation curves were also measured aperiodically over the narrow resonance at 4.58 MeV. All checks indicated that the energy shifts were less than 5 keV.

III. EXPERIMENTAL RESULTS

The 0° excitation curves reported for the ^{13}C(α, n) reaction by various groups show essentially the same resonant structure. However, differences of 50 to 100 keV in the quoted energy scales are generally noted. As it is desirable to measure the polarization angular distributions at the same energy relative to the structure as were the previous differential cross-section measurements, we, too, measured a 0° yield curve, using the helium scintillator as the neutron detector. Our measurements are in close agreement with those of WCB at the lower energies and with those of KMR at the higher energies, and hence the differential cross-section data reported by these groups are used in our analysis. Slight differences in the energy scales are, however, present and these differences will be reflected in the energies quoted by the appropriate investigator, although they do correspond to the same energy relative to the structure. Although a precise determination of the energy scale would be highly desirable, no such attempt was made in the present work. Bair and Haas[15] are, however, currently attempting to establish an absolute energy calibration via their measurements of the energy dependence of the total neutron yield from this reaction.

In the present work, polarization excitation curves were measured at laboratory angles of 25 and 105° for the energy interval between 2.9 to 3.6 MeV, and at 15° for the energy interval between 4.08 and 4.90 MeV. Only the latter curve showed much structure and this is shown in Fig. 4, together with the 0° cross-section excitation curve of KMR. Angular distributions of the polarization measured at six average α-particle energies of 3.36, 4.36, 4.42, 4.58, 4.70, and 4.80 MeV are shown in Figs. 5–10. Measurements were generally made using target thicknesses less than the width of the resonance under investigation. Also shown in Figs. 5–10 are the differential cross-section data of WCB and KMR, together with the calculated fits to the data discussed below. No measurements were made in the 3.36- to 4.36-

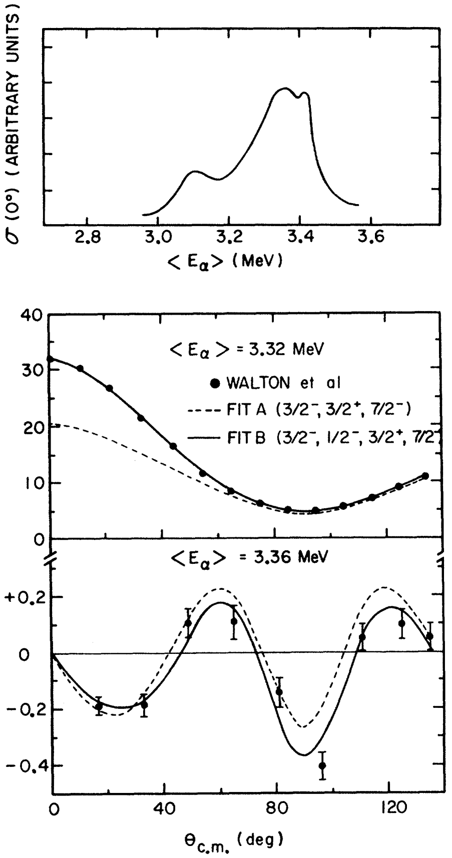

FIG. 5. A 0° cross-section excitation curve is shown at the top of this figure and is taken from WCB. $\sigma(\theta)$ of WCB and the present polarization measurements are shown in the lower portion of the figure, together with the calculations discussed in the text.

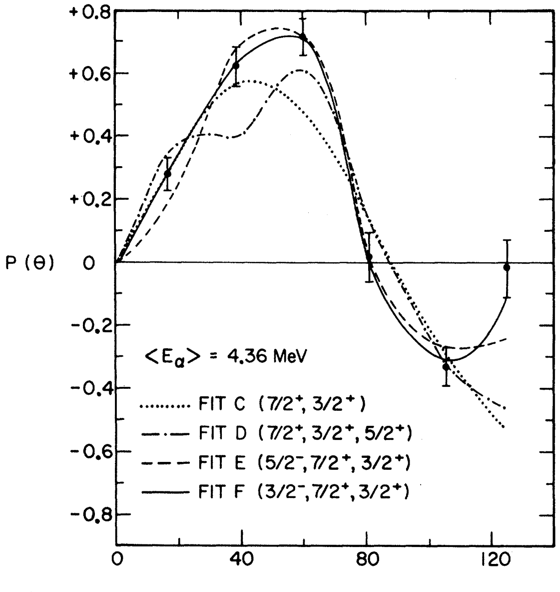

FIG. 6. The polarization angular distribution measured at 4.36 MeV, together with the fits to the data as discussed in the text. The J^π values included in the calculations for each fit are as indicated.

MeV interval, because of very low reaction cross sections. The differential cross sections shown in Figs. 5–10 were reconstructed from the Legendre-polynominal coefficients given by the respective investigators but are shown as dots in the figures for clarity in comparison with the theoretical calculations. Towards the end of the analysis discussed below, RSS reported their 0° excitation-curve measurements covering the 4.48- to 10.46-MeV energy range. No $\sigma(\theta)$ data were measured by these authors below 4.995 MeV. In the region of interest here, the absolute values of $\sigma(\theta)$ reported by KMR are 2 to 3 times *larger* than those of RSS. Although such a discrepancy in magnitude could affect conclusions drawn by KMR if his absolute calibration is in error, the analysis discussed below is independent of the absolute magnitude. Numerical tables of the polarization data are on file with the American Documentation Institute (ADI)[16] as Document No. 01272.

IV. REACTION ANALYSIS

The polarization data were analyzed simultaneously with existing cross-section data to make J^{π} assignments to levels in ^{17}O. The neglect of all mechanisms other than compound-nucleus formation was justified because of the obvious dominance of this mode in the cross section and because the recent calculations of RSS have indicated that direct-reaction contributions are expected to be quite small in this energy range. The initial calculations made using the usual Breit-Wigner single-level formalism were, however, unsuccessful in that a satisfactory description of the data required that three, and frequently four, resonances had to be included in the calculations, particularly to describe the polarization data. $P(\theta)$ is, of course, sensitive to all of the contributing matrix elements, even those arising from far-off resonances. A reasonably accurate determination of the "hard-sphere scattering" phase shifts is necessary for the above type of calculations. As the usual hard-sphere phase shifts must be modified to include contributions from all states not considered explicitly in the calculations, these phase shifts must be evaluated in an energy region devoid of resonant structure, a situation that does not prevail here. Because the main goal of this work was to make J^{π} assignments, this method was discarded in favor of a more general approach similar to that used previously by Darden and co-workers.[17]

In the latter method, a computer code is used to search for the amplitude and phases of those S-matrix elements $S^{J^{\pi}}(s'l'\alpha'; sl\alpha)$ contributing to the reaction which lead to the best simultaneous description of the differential cross section and polarization angular distribution at each energy. The general expressions given by Welton[18] are used to calculate the cross sections and polarizations, as

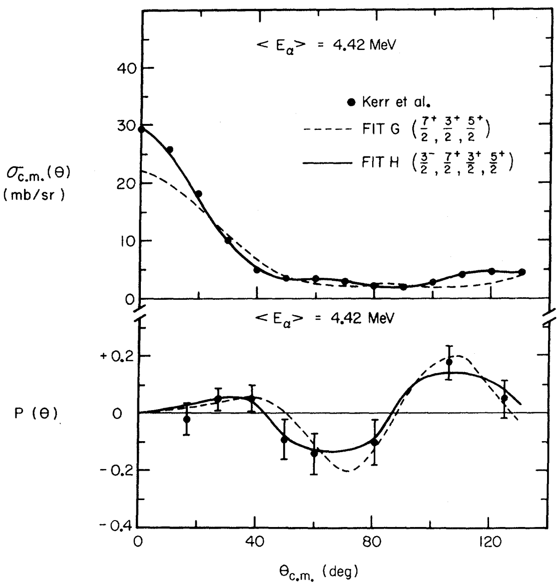

FIG. 7. The differential cross section of KMR and the present polarization measurements are shown together with the fits discussed in the text. Also, see caption for Fig. 6.

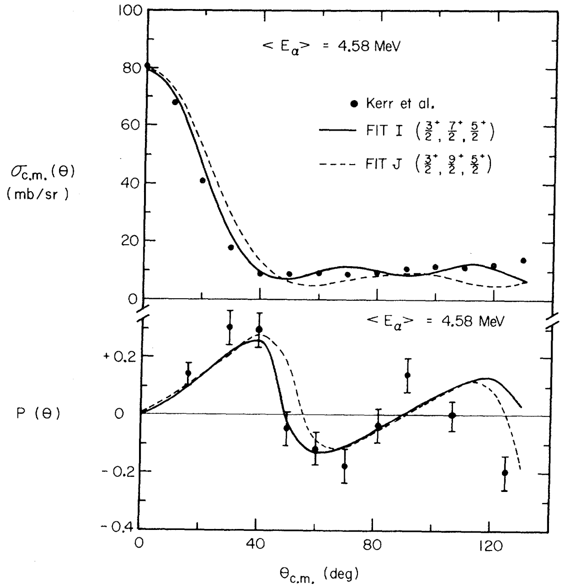

FIG. 8. The differential cross section of KMR and the present polarization measurements for the very narrow resonance at 4.58 MeV, together with the fits discussed in the text.

discussed by Marr, Kuenhold, and Donoghue.[19] The cross sections and polarizations are calculated using trial input parameters and then compared with the experimental data, after which some of the amplitudes and/or phases of those matrix elements corresponding to the levels that are the probable contributors to the reaction are varied. A direct search procedure is used to find a minimum in the quality of fit parameter χ^2, where

$$\chi^2 = \frac{1}{I}\sum_{i=1}^{I}\left[\frac{\sigma_{\text{exp}}(\theta_i) - \sigma_{\text{calc}}(\theta_i)}{\Delta\sigma(\theta_i)}\right]^2 + \frac{1}{J}\sum_{j=1}^{J}\left[\frac{P_{\text{exp}}(\theta_j) - P_{\text{calc}}(\theta_j)}{\Delta P(\theta_j)}\right]^2 .$$

Here, I and J are the number of data points in the respective angular distributions. Trial input parameters were initially calculated using a single-level formalism, but reasonable variations on these parameters were tried to insure that an absolute minimim in χ^2 had been reached for that combination of levels. A more complete description of the computer program and the procedures used in varying the parameters is given by Marr, Kuenhold, and Donoghue.[19] The direct search routine STEPIT was written by Chandler.[20]

Although good fits to the data were generally obtained using previously determined J^π assignments, the calculations were extended in an effort to locate alternate sets of levels that might provide equally good descriptions of the data, so that the uniqueness of the parameters could be determined. Levels formed by $l \leq 5$ units in either the entrance or exit channel were tried, thereby restricting the total number of levels of different J^π values considered to 10. All reasonable combinations of level assignments could therefore be tried, insuring that the best description of the data was achieved and that the assignments arrived at were most probably unique. Although the analysis discussed below is capable of making J^π assignments to the states contributing to the reaction, the explicit identity of the state(s) to which these assignments correspond is not directly given. However, as the amplitudes of the individual S-matrix elements themselves exhibit an energy-dependent resonance shape, this information is gained in a straightforward manner by first determining the amplitudes of all matrix elements over an energy range and then correlating the energy-dependent structure of these amplitudes with the experimental resonance structure.

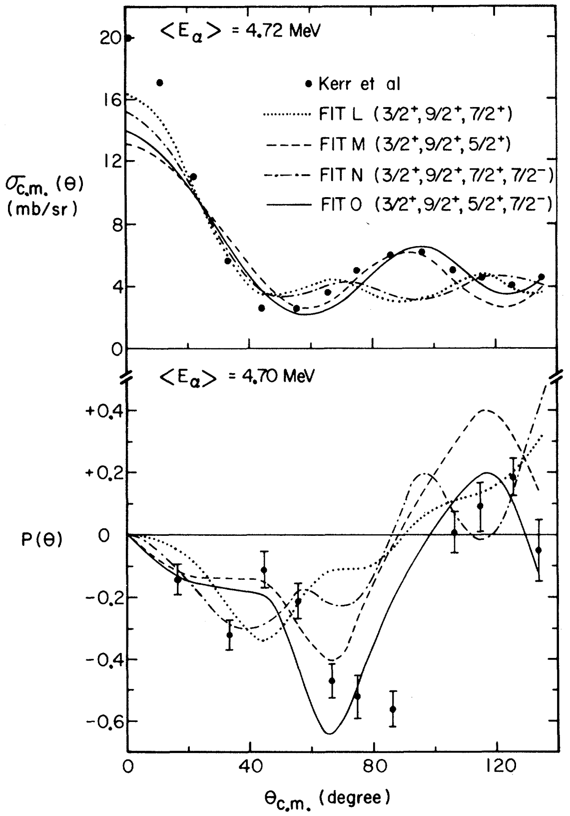

FIG. 9. The differential cross section of KMR and the present polarization measurements for the 4.7-MeV resonance together with the fits discussed in the text.

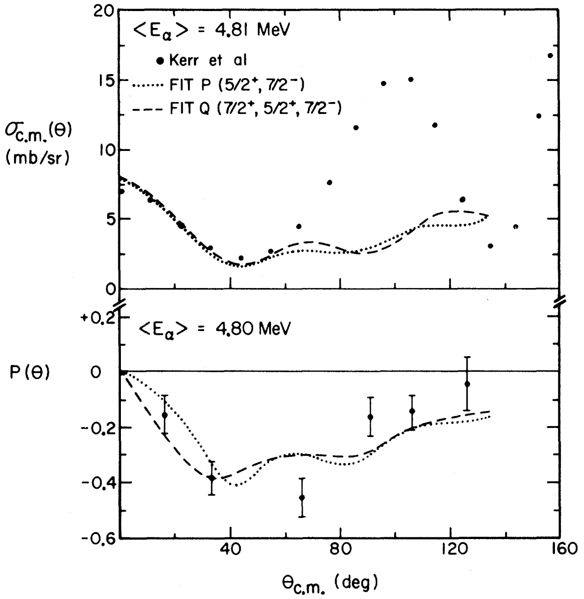

FIG. 10. The differential cross section of KMR and the present polarization measurements at 4.80 MeV together with the fits discussed in the text.

Most of the calculations were made using the cross-section data of KMR but, as noted above, the magnitudes of their cross sections are two to three times greater than recently reported by RSS. All final calculations were therefore repeated with $\sigma(\theta)$ renormalized to the values quoted by RSS. In no case were the conclusions reached here affected by this uncertainty in the normalization.

Towards the end of the present analysis, an ambiguity in the absolute parity assignments that can be made from an analysis of the (α, n) data, *even when polarization data are included*, was discovered. In particular, identical descriptions of $\sigma(\theta)$ and $P(\theta)$ result when the parities of all participating states are reversed, if, simultaneously, the sign of the phases of the S^{J^π} are also reversed. The relative parities of the contributing states (usually three or four states in the present analysis) can, however, still be determined so that if the parity of one of these states is established via such measurements as (α, α) scattering or n-^{16}O scattering, the parities of all states are known. As some of the parities have been so established, the fits to the data discussed below are believed to be correct. This parity ambiguity[21] is discussed in more detail by Donoghue *et al.*[9] and by Seyler.[22] Separate discussions of the reaction data at each energy in the α-particle energy range from 3.36 to 4.8 MeV are presented below.

A 0° yield curve for E_α between 3.0 and 3.6 MeV, illustrated in Fig. 5, shows that three levels contribute here with resonance energies of 3.1, 3.36, and 3.42 MeV. Previous work has resulted in a favored J^π level sequence of $\frac{3}{2}^-$, $\frac{3}{2}^+$, and $\frac{7}{2}^-$ for these states, although because of the ambiguities cited above the alternative parity sequence was not completely excluded. There is also some evidence that a broad $J=\frac{1}{2}$ state contributes here and this has been placed near 3.1 MeV by Schiffer, Kraus, and Risser (SKR).[1] A polarization angular distribution measured at 3.36 MeV is shown in Fig. 5, together with a reconstructed differential cross section from WCB.[3] The best three-level search calculation (fit A) shown here was achieved using the favored J^π assignments cited above. The fit to the data was considerably improved, however, when a fourth level with $J^\pi=\frac{1}{2}^-$ was included in the calculations, together with the $\frac{3}{2}^-$, $\frac{3}{2}^+$, and $\frac{7}{2}^-$ states, as is shown by fit B. Although an identical description of the data is provided with a $\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{3}{2}^-$, $\frac{7}{2}^+$ sequence, Barnes, Belote, and Risser[5] have established via (α, α) measurements that the parity sequence shown in Fig. 5 is correct. The previously suggested assignments (see fit B) including the fourth state, are certainly in excellent agreement with the data.

In the energy interval between 4.3 and 5.0 MeV, four prominent resonances are apparent, as shown in Fig. 4, although several additional states also appear to contribute in this region. To investigate the lowest energy resonance, a polarization angular distribution was measured at 4.36 MeV, as shown in Fig. 6. In the absence of $\sigma(\theta)$ data here, search calculations on $P(\theta)$ alone were made, using results from higher-energy calculations as a guide. Four of the better fits to the data are shown in Fig. 6, each of which includes the $\frac{7}{2}^+$-$\frac{3}{2}^+$ level combination deduced by KMR as corresponding to the 4.4-MeV ($\Gamma=21$ keV) and 4.42-MeV ($\Gamma=80$ keV) resonances. The best fit to the data was obtained with a $\frac{3}{2}^-$ assignment for a third state (fit F) while a slightly poorer fit was achieved assuming a $\frac{5}{2}^-$ third-state assignment (fit E). Some evidence[2] for a $\frac{3}{2}^-$ state has previously been seen in ^{13}C(α, α) and ^{13}C(α, n) work at 4.18 MeV. KMR established that the parity of the $\frac{7}{2}$ state was positive from (α, α) scattering. The main contributions to the reaction here are $\frac{7}{2}^+$ and $\frac{3}{2}^+$, as previously deduced. The assumption of a third state of $J^\pi=\frac{3}{2}^-$ is required to describe these data, as well as the data at higher energy. This state, which is unresolved in the yield curve, is apparently broad and it is not clear where to place it without additional investigation.

Measurements of $P(\theta)$ at 4.42 MeV are shown in Fig. 7 along with $\sigma(\theta)$ reconstructed from KMR. The best search calculations shown here all include the $\frac{7}{2}^+$-$\frac{3}{2}^+$ pair of levels noted above. These two levels alone do not describe the data very well. The fit to the data was improved considerably when a $\frac{5}{2}^+$ state was included (see fit G). However, a satisfactory fit to the data was obtained only when the $\frac{3}{2}^-$ state noted above was also included in the calculations. The $\frac{5}{2}^+$ state was later identified as corresponding to the 4.7-MeV resonance and, as noted below, this assignment differs from that made by KMR.

The narrow resonance at 4.58 MeV ($\Gamma=15$ keV) was investigated using a 30-keV-thick target, the thinnest target considered practical for double-scattering measurements. Previous investigators[1,2] have made a tentative $\frac{9}{2}^+$ assignment to this state, but a $\frac{7}{2}^+$ assignment could not be excluded. Two of the many three- and four-level calculations made in attempting to describe this data are shown in Fig. 8. As is seen here, it is not possible to choose between these two assignments as fits I and J are better in describing different angular regions of both $\sigma(\theta)$ and $P(\theta)$. The inclusion of a fourth state in the calculations did not improve the fits appreciably and hence have not been shown here. Of importance here, the amplitude of the $\frac{5}{2}^+$ state is quite large for both of these fits and is consistent with assigning this J^π

value to the 4.7-MeV resonance. Fits to the data that did not include this assignment were appreciably worse.

In their investigation of the broad anomaly near 4.7 MeV, KMR showed that their ^{13}C(α, n) $\sigma(\theta)$ data were qualitatively described by assuming either a $\frac{5}{2}^+$ or $\frac{7}{2}^+$ assignment for this state, although neither fit was very good. However, on the basis of (α, α) scattering data at two backward angles, these authors concluded that the state was $\frac{7}{2}^+$, although no detailed calculations were given. Our attempts to reproduce the data, shown in Fig. 9, included a large number of three- and four-level search calculations, with the four most relevant ones (fits L through O) shown in the figure. The states included in the calculations are $\frac{3}{2}^+$ (at 4.42 MeV), $\frac{9}{2}^+$ (at 4.58 MeV), and a third state at 4.7 MeV of $\frac{7}{2}^+$ (fit L) or $\frac{5}{2}^+$ (fit M). Although the latter fit is the better of these, there are enough discrepancies that additional states known to exist at slightly higher energies were then included. Of these, a fourth state of $J^\pi = \frac{7}{2}^-$ produced by far the best agreement with the data. This state is noted both by KMR and in the more recent sophisticated analysis of RSS and is reported to be very close to $E_\alpha = 5$ MeV. The fit to the data with the $\frac{5}{2}^+$ assignment for the 4.7-MeV resonance is considerably better than that with the $\frac{7}{2}^+$ assignment, as was the case noted at 4.42 and 4.58 MeV, from which we conclude that the resonance is of $\frac{5}{2}^+$ character. Although the fits to the data are still not perfect, additional states known to exist near 5 MeV have of necessity been excluded because of the difficulties associated with five-, six-, or seven-level calculations.

Measurements were also made at 4.8 MeV (see Fig. 10) in an attempt to gain some insight into the complicated structure at higher energy, as well as to check lower-energy assignments. Although numerous search calculations were made including contributions from up to four levels, it was never possible to describe $\sigma(\theta)$, particularly the large bump at backward angles. It was, however, fairly easy to reproduce the polarization data using level assignments made by RSS and KMR. The fits shown in this figure are the best that could be achieved when attempting to fit $\sigma(\theta)$ and $P(\theta)$ simultaneously. As the shape of this cross section at 4.8 MeV is quite anomalous compared with that at slightly lower and higher energies, the coefficients quoted by KMR from which $\sigma(\theta)$ are calculated might be in error here. An

TABLE I. A summary of resonances observed in ^{13}C$+\alpha$ and ^{16}O$+n$.

		^{13}C$(\alpha,n)^{16}$O and ^{13}C$(\alpha,\alpha)^{13}$C reactions				
E_α (MeV)	E_x (^{17}O) (MeV)	Present work J^π	SKR (Ref. 1) J^π (Γcm) [a]	KMR (Ref. 2) J^π (Γcm)	WCB (Ref. 2) J^π (Γcm)	^{16}O$(n,n)^{16}$O Fossan *et al.* [b] J^π (Γcm)
3.10	8.70	$\frac{3}{2}^-$	$\frac{3}{2}^\pm$ (69)		$\frac{3}{2}^\pm$ (85)	$\frac{3}{2}$ (55)
(~3.1)	...	$\frac{1}{2}^-$	$\frac{1}{2}^\pm$			
3.36	8.92	$\frac{3}{2}^+$	$\frac{3}{2}^\mp$ (115)		$\frac{3}{2}^\mp$ (110)	
3.42	8.96	$\frac{7}{2}^-$	$\frac{7}{2}^\pm$ (23)		$\frac{7}{2}^\pm$ (35)	$\frac{7}{2}$ (28)
3.64	9.14		(6)	$\frac{1}{2}^-$ (6)		$\geqslant\frac{3}{2}$ (<17)
3.69	9.18			$\frac{7}{2}^-$ (3)		
3.72	9.20		$\frac{5}{2}$ (4)	$\frac{5}{2}^+$ (5)		$\geqslant\frac{3}{2}$ (140)
4.11	9.50		$\frac{7}{2}$ (11)	$\frac{5}{2}^-$ (15)		
(~4.3)	...	$\frac{3}{2}^-$				
4.38	9.70	$\frac{7}{2}^+$	$\frac{7}{2}$ (19)	$\frac{7}{2}^+$ (16)		$\geqslant\frac{5}{2}$ (28)
4.42	9.74	$\frac{3}{2}^+$	(53)	$\frac{3}{2}^+$ (61)		$\geqslant\frac{3}{2}$ (28)
4.58	9.86	($\frac{9}{2}^+$)	$\frac{9}{2}$ (11)	$\frac{9}{2}^+$ (12)		$\geqslant\frac{1}{2}$ (25)
4.70	9.95	$\frac{5}{2}^+$	($\frac{5}{2}$, $\frac{7}{2}$) (153)	$\frac{7}{2}^+$ (107)		
4.94	10.14			$\frac{5}{2}^+$ (138) [c]		
4.98	10.17	($\frac{7}{2}^-$)		$\frac{7}{2}^-$ (46) [c]		

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alternate explanation would be that additional levels must be included in the calculations, as it is well established that the region around 5 MeV and higher is quite complicated.

V. SUMMARY

A summary of the J^π assignments resulting from the present analysis is presented in Table I together with some of the previous results from analyses of $^{13}C+\alpha$ and $^{16}O+n$ reactions. Except for the reassignment of $J^\pi=\frac{5}{2}^+$ to the state at 9.95 MeV, the majority of the previous level assignments are confirmed by this work. In addition, the existence of two broad levels noted previously in cross-section work near 3.1 and 4.3 MeV has been supported by the present analysis. The present work has shown that neutron polarization measurements can be of significant value in making spectroscopic assignments to compound-nucleus levels, particularly when the level structure is complicated by overlapping level structure. The method used appears to be successful even when as many as four levels contribute to the reaction at a specific energy. It is doubtful, however, that additional states could be suitably accommodated, because of the large number of variable parameters that would enter the calculations.

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†Present address: U. S. Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico.

‡National Defense Education Act Graduate Fellow.

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