Natural Parity States of O^{16} at 11.09 and 12.05 MeV*

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The elastic scattering of alpha particles from C^{12} has been used to measure the spins, parities, and widths of two previously unassigned states of O^{16}. These levels at excitation energies of 11.094 ± 0.006 and 12.050 ± 0.008 MeV were found to have $J^\pi=4^+$ and 0^+, respectively, and center-of-mass widths of 0.3 ± 0.1 and 1.5 ± 0.5 keV, corresponding to values of the dimensionless reduced width $\theta_\alpha^2=10^{-3}$ and 4×10^{-4}.

INTRODUCTION

TWO low-lying states of O^{16} have not previously been given spin-parity assignments. One of these is a member of the doublet (11.080 and 11.096 MeV) found in a recent survey of O^{16} states by Browne and Michael[1] using the reaction $N^{14}(He^3,p)O^{16}$. The other is the state at 12.05-MeV excitation. [1–3] Experimental data pertinent to these assignments present a confusing aspect.

A state at 11.08 ± 0.03 MeV was identified as being either 2^- or 3^+ by Hornyak and Sherr[4] using $O^{16}(p,p'\gamma)O^{16}$ coincidence results. The assignment of 3^+ for an unnatural[5] parity state in this energy region was confirmed by Kuehner *et al.*[6,7] using $N^{14}(He^3,p\gamma\gamma)O^{16}$. Squires *et al.*[8] found a group from $F^{19}(p,\alpha)O^{16*}$ corresponding to a state at 11.085 ± 0.014 MeV with a width of 25–30 keV, which is to be compared to an instrumental resolution of 20 keV for the group to the narrow 9.85-MeV level. In retrospect, it would appear that Squires *et al.*[8] may have had comparable contributions from both the 11.080- and 11.096-MeV states, thus explaining the large observed width. Weil *et al.*[9] found a neutron threshold in $N^{15}(d,n)O^{16*}$ corresponding[10] to a level at 11.078 ± 0.015 MeV which they thought might not be an unnatural parity state. This left unexplained the weak anomaly observed at $E_x=11.11\pm0.02$ MeV[10] in the $C^{12}(\alpha,\alpha)C^{12}$ data of Bittner and Moffat.[11] The discovery that this region contains two levels suggests that the unassigned state is the natural parity state[5] seen by Bittner and Moffat,[11] while the other is the 3^+ unnatural parity state found by Kuehner.[6,7]

The state at 12.05 MeV has also been observed through several reactions.[2,3] Hornyak and Sherr[4] found that it did not show strong gamma radiation in $O^{16}(p,p'\gamma)O^{16}$ coincidence measurements, in contrast to the behavior of nearby 2^- and 3^+ states, but they felt that there was some evidence for weak gamma-ray emission—suggesting an unnatural parity state. Nevertheless, the study of unnatural parity states by Bromley *et al.*[7] using the $N^{14}(He^3,p\gamma)O^{16}$ reaction failed to produce any evidence for this level, even though this state is now known to be excited by $N^{14}(He^3,p)O^{16}$ (Ref. 1). Bittner and Moffat[11] found no evidence for a narrow natural parity state in this energy region from their $C^{12}(\alpha,\alpha)C^{12}$ data. More recently, Bishop *et al.*[12] using $O^{16}(e,e')O^{16*}$ described this state as 2^+ while Harvey *et al.*[13] concluded from $O^{16}(\alpha,\alpha')O^{16*}$ that the level has negative parity (although the latter authors would not discard completely a 1^+ assignment suggested by the alpha-particle model).

States near 11.1 and 12.05 MeV did not produce a significant amount of ground-state radiation from the $C^{12}(\alpha,\gamma)O^{16}$ reaction.[14] This, by comparison with relatively strong yields from the nearby 11.52- and 12.44-MeV states, would imply that neither 2^+ nor 1^- states are present[15]; however, between $E_x=11.098\pm0.008$ and 11.104 ± 0.008 MeV the excitation curves for ground-state and 6.92-MeV gamma rays show a small step in the yield while the excitation curves for 6.13- and 7.12-MeV gamma rays remain unchanged, suggesting a weak cascade through the 6.92-MeV, 2^+ state. (Simultaneous detection of both cascade members would account for an apparent increase in the ground-state yield.) Any cascade radiation associated with the 12.05-MeV state was completely obscured by intense 6- and 7-MeV radiation from $C^{13}(\alpha,n\gamma)O^{16}$ (Ref. 16).

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[5] Natural parity states are defined here as having $J^\pi=0^+$, 1^-, 2^+, 3^-, etc. (i.e., even parity with even spin—odd parity with odd spin). All other assignments are defined as unnatural parity states.
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EXPERIMENTAL PROCEDURE

It was decided to remeasure the $C^{12}(\alpha,\alpha)C^{12}$ reaction with sufficient resolution to identify any narrow, natural parity states corresponding to excitations near 11.1 and 12.05 MeV in O^{16}. Beams of He^{2+} were obtained from the ONR-CIT tandem accelerator and used to bombard self-supporting natural carbon foils of ≈ 10 $\mu g/cm^2$. Elastically scattered alpha particles were detected by two Ortec silicon, surface-barrier detectors. The two detectors were independently movable in a horizontal plane about the target and subtended angles of approximately $\frac{1}{2}°$ and 1°, respectively, in the laboratory system. Laboratory angles were determined to ±0.3°. Target and detectors were housed in a 61-cm-diam evacuated scattering chamber. Signal pulses were amplified by conventional charge-sensitive preamplifiers and stored simultaneously in two 100-channel quadrants of a 400-channel pulse-height analyzer. Beam currents of typically 0.1–0.3 μA of He^{2+} passed through the target and were stopped in a Faraday cup. Energy excitation functions were run at each pair of counter angles with a total integrated charge of either 15 or 45 μC per data point.

EXPERIMENTAL RESULTS

The 11.09-MeV State

Shown in Fig. 1 are excitation curves for $C^{12}(\alpha,\alpha)C^{12}$ at selected center-of-mass angles for bombarding energies corresponding to excitations near 11.1 MeV in O^{16}. At 171.3° the resonance resembles that observed by Bittner and Moffat[11]; moreover, at center-of-mass angles of 90.0°, 122.6°, 125.3°, 140.8°, and 155.0°, corresponding respectively to zeros of the Legendre polynomials P_{odd}, P_5, P_2, P_3, and P_5, a definite resonant structure is also evident, indicating that this natural parity state has neither 2^+, 3^-, 5^-, nor any odd value of the spin. However, at three angles, 70.1°, 109.9°, and 149.4°, where the polynomial P_4 is zero, no resonance appears, establishing this state as 4^+.

A kinematic check of the energy of the scattered particles as a function of angle and bombarding energy showed the target nuclei that produced the resonance to be consistently mass 12 with deviations of less than 0.1 mass unit. The bombarding energy at this resonance was found to be $E_\alpha = 5.245 \pm 0.008$ MeV corresponding[10] to an excitation energy $E_x = 11.094 \pm 0.006$ MeV. This is in agreement with the fragmentary $C^{12}(\alpha,\gamma)O^{16}$ data in this region[14,15] and implies that the 4^+ state corresponds to the level found at 11.096 ± 0.003 MeV by Browne and Michael.[1]

The 12.05-MeV State

Excitation curves of $C^{12}(\alpha,\alpha)C^{12}$ near $E_x = 12.05$ MeV (Fig. 2) all display a definite resonant structure. Among the center-of-mass angles included in Fig. 2 are 54.7°, 70.1°, 90.0°, 109.9°, 122.6°, 125.3°, 131.4°, 140.8°, and 158.8°, zeros of the Legendre polynomials P_2, P_4, P_{odd}, P_4, P_5, P_2, P_6, P_3, and P_6, respectively, indicating that this natural parity state has neither 2^+, 4^+, 6^+ nor any odd spin. The choice remaining is 0^+ since a spin of 8 or higher is most unlikely for this region of excitation.

Again, kinematic checks indicated that the resonance was produced by target nuclei with a mass of 12. The resonance energy was determined to be $E_\alpha = 6.518 \pm 0.010$ MeV, corresponding[10] to $E_x = 12.050 \pm 0.008$ MeV.

ANALYSIS

A calculation of resonance shapes was undertaken to substantiate the 0^+ assignment of the 12.05-MeV state

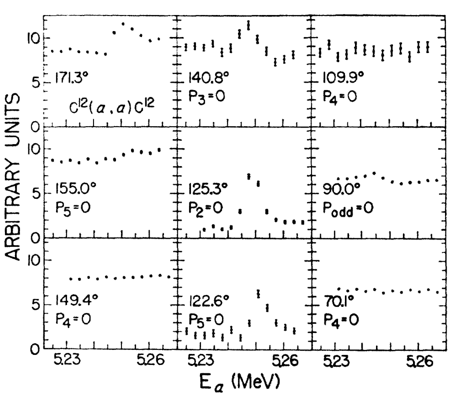

FIG. 1. Excitation curves for the elastic scattering of alpha particles from C^{12} at nine center-of-mass angles. The observed anomaly corresponds to a narrow 4^+ state of O^{16} at $E_x = 11.09$ MeV. Ordinates for all curves should be regarded as independent of one another. Statistical errors are indicated where they exceed the size of the data points.

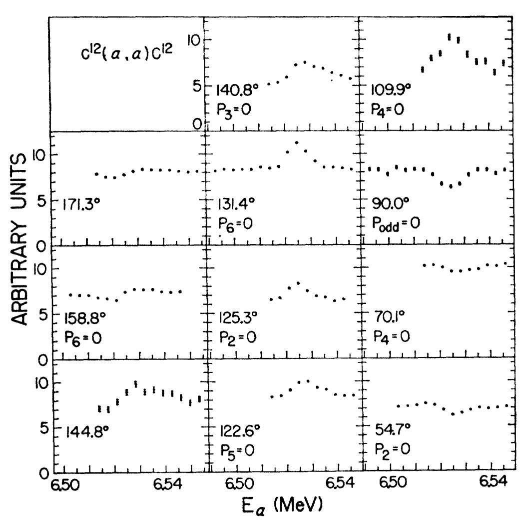

FIG. 2. Excitation curves for the elastic scattering of alpha particles from C^{12} at eleven center-of-mass angles. The observed anomaly corresponds to a narrow 0^+ state of O^{16} at $E_x = 12.05$ MeV. Ordinates for all curves should be regarded as independent of one another. Statistical errors are indicated where they exceed the size of the data points.

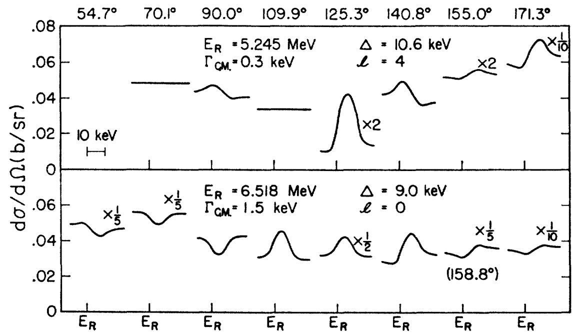

FIG. 3. Calculated resonance shapes for the elastic scattering of alpha particles from C^{12}. Curves are shown for center-of-mass angles corresponding to most of the experimental measurements. For these calculations E_R refers to the resonance energy in the laboratory system, $\Gamma_{c.m.}$ is the intrinsic center-of-mass width of the level, l is the orbital angular momentum, and Δ is the experimental resolution in the laboratory system (full width at half-maximum).

and also to provide an indication of the total widths of the two states investigated. The background phase shifts from nearby broad states of O^{16} were determined by starting with the phase shifts δ_0 through δ_4 obtained by Jones *et al.*[17] for energies below $E_\alpha = 4.8$ MeV and then continuing the analysis through $E_\alpha = 6.8$ MeV using the data of Bittner and Moffat.[11] While this procedure is not completely unique because of the limited number of angular measurements available, it is interesting to observe that the very broad 0^+ level introduced near $E_\alpha = 5.5$ MeV by Bittner and Moffat[11] was not indicated by the present analysis—however, the *S*-wave phase shift deduced is much less negative than would be expected from a purely hard-sphere energy variation. The background phase shifts δ_0 through δ_4 found by thit procedure were $-18°$, $126°$, $2.5°$, $30.5°$, and $177°$ as $E_\alpha = 5.25$ MeV and $-31°$, $117°$, $171.5°$, $124°$, and $174.5°$ at $E_\alpha = 6.52$ MeV.

Based on these background phase shifts the resonance shapes were calculated assuming very narrow resonances with $l = 4$ at $E_\alpha = 5.25$ MeV and $l = 0$ at $E_\alpha = 6.52$ MeV. Quantitative examination of these calculations indicates that both resonances are considerably narrower than the instrumental resolution of this experiment. Comparison of the observed shapes and the calculated shapes into which has been folded the experimental resolution permits total widths $\Gamma_{c.m.} = 0.3 \pm 0.1$ and 1.5 ± 0.5 keV to be attributed, respectively, to the O^{16} states at 11.09 and 12.05 MeV.

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TABLE I. Level parameters for the resonances investigated. E_α refers to the laboratory bombarding energy, E_x is the excitation energy in O^{16}, $\Gamma_{c.m.}$ is the center-of-mass width of the level, and θ_α^2 is the dimensionless reduced width defined as in Ref. 11 or 17 for a radius of 5.43 F.

E_α (lab) (MeV)	E_x (MeV)	J^π	$\Gamma_{c.m.}$ (keV)	θ_α^2	Browne and Michael E_x (MeV)
3.585 ± 0.006	9.850 ± 0.004				9.847 ± 0.003
5.245 ± 0.008	11.094 ± 0.006	4^+	0.3 ± 0.1	10^{-3}	11.096 ± 0.003
6.518 ± 0.010	12.050 ± 0.008	0^+	1.5 ± 0.5	4×10^{-4}	12.053 ± 0.003

Figure 3 displays a sample of these calculated shapes for typical values of the experimental resolution. The excellent agreement between the curves in Fig. 3 and the scattering data (Figs. 1 and 2) provides confirmation for the 4^+ and 0^+ assignments given to these states at 11.09 and 12.05 MeV, respectively.

DISCUSSION

This experiment assigns to natural parity states of O^{16} at 11.09 and 12.05 MeV spins and parities of 4^+ and 0^+, respectively. The 4^+ state is found to correspond to the 11.096-MeV state of Browne and Michael[1] implying that their 11.080-MeV state is the 3^+ resonance identified by Kuehner *et al.*[6] Table I lists, in the first five columns, properties of these states obtained by the present experiment. For comparison, the last column in Table I contains the excitation energies determined for these resonances by Browne and Michael.[1] The narrow 9.85-MeV, 2^+ resonance is included as a cross check on the energy calibration.

Preliminary results from a concurrent experiment by Jones and Parker[18] using $N^{14}(He^3,p)O^{16*}(\alpha)C^{12}$ particle-particle correlation techniques find the 11.09-MeV state to have a spin of 2 or higher and are therefore consistent with the present 4^+ assignment. However, Jones and Parker[18] also find some indication for a spin of 2 or higher for the 12.05-MeV state, in disagreement with the present 0^+ assignment.

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[18] K. W. Jones and P. D. Parker (private communication).