Elastic Scattering of Alpha Particles by Carbon*

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By using a propane gas target and 4.0- to 7.6-Mev alpha particles from an electrostatic generator the elastic scattering differential, cross section of carbon has been measured with high resolution at five angles. A phase-shift analysis of the data indicates levels in O^{16} with the following energies, angular momenta, and parities: 10.36 Mev, $J=4$, $+$; 11.25 Mev, $J=0$, $+$; 11.51 Mev, $J=2$, $+$; 11.62 Mev, $J=3$, $-$; and 12.43 Mev, $J=1$, $-$. Reduced widths of the 10.36, 11.25, and 11.62 Mev levels approach the Wigner limit for single-particle excitation. Comparison is made with levels predicted by the alpha-particle nuclear model.

I. INTRODUCTION

THE study of a variety of reactions involving O^{16} has permitted assignment of numerous energy levels in that nucleus.[1] One of these processes is the elastic scattering of alpha particles by C^{12}, in which the compound nucleus O^{16*} is an intermediate state. In the light of dispersion theory,[2] anomalies in the elastic differential scattering cross section may be interpreted in terms of energy levels of the compound nucleus. Elastic scattering is a particularly desirable method for levels below 11.6 Mev in O^{16} since no other reactions can compete with the elastic scattering to cause ambiguity in the determination of level widths.

Hill[3] has reported such a scattering experiment performed with high resolution in the energy range 0.5 to 4.0 Mev. Resonances lying immediately above this range have been reported[4] but assignment of angular momenta and widths was not possible because of limitations in resolution. Recently a new He^{++} ion source[5] in the Wisconsin electrostatic generator has made available a beam of doubly charged alpha particles with energy up to 7.6 Mev. It seemed desirable therefore to extend the high-resolution experiments beyond 4 Mev.

Since C^{12} and He^4 are both nuclei of zero spin, the compound nucleus can be formed only in states with parity and total angular momentum equal to those of the colliding pair. Thus only O^{16} states with parity and angular momentum both even or both odd will be detected by elastic scattering.

II. EXPERIMENTAL PROCEDURE

The doubly charged alpha-particle beam from the electrostatic generator was passed through the magnetic and 90° electrostatic analyzer, which was operated at 0.15 percent energy resolution, i.e., full width at half-maximum intensity. The beam then entered a differentially pumped scattering chamber containing the propane gas target and was collected in a Faraday cup for integration. This apparatus has been described in the literature.[6]

Two proportional counters, separated from the target gas by side windows of 0.01-mil Ni foil, were used simultaneously to detect the alpha particles scattered at two angles. Pulse height was monitored with the aid of an oscilloscope and the discrimination level was set to avoid counting small noise and background pulses. For most of the energy range, an additional 0.02-mil Al foil was placed over the forward angle counter to stop recoil protons from the propane.

For convenience in analysis of the data four center-of-mass angles were selected for which the Legendre polynomials of order one to four vanish. These angles were: 147.9°, 140.8°, 123.2°, and 90.0°; at which vanish (or nearly so) the polynomials of order: $l=4$, $l=3$, $l=2$, and both $l=1$ and 3, respectively. At the extreme back angle of 171.2° all partial waves contribute to the scattering.

The propane gas pressure was varied between 0.25 and 1.1 cm Hg, depending on the magnitude and rate of variation of the scattered intensity. For 6-Mev alpha particles these pressures produced an effective target thickness of from 2.5 to 10 kev at 90° and 10 to 45 kev at 171.2°.

In order to make corrections for energy lost by the beam between the differential pumping entrance slits and the target volume, the resonances at 4.3 and 7.0 Mev were measured using various gas pressures. It was assumed that the beam energy loss was proportional to the gas pressure, for a given incident energy. This permitted calculation of the energy loss per unit gas pressure at the two energies 4.3 and 7.0 Mev. Since these rates were proportional to Bethe's[7] energy-loss cross section curves for alpha particles at these energies, the same proportionality was assumed for all incident energies. Energy loss in traversing the chamber varied with gas pressure and energy from 30 to 160 kev. At no energy is the uncertainty in energy greater than 10 kev. The 0.15 percent resolution of the electrostatic

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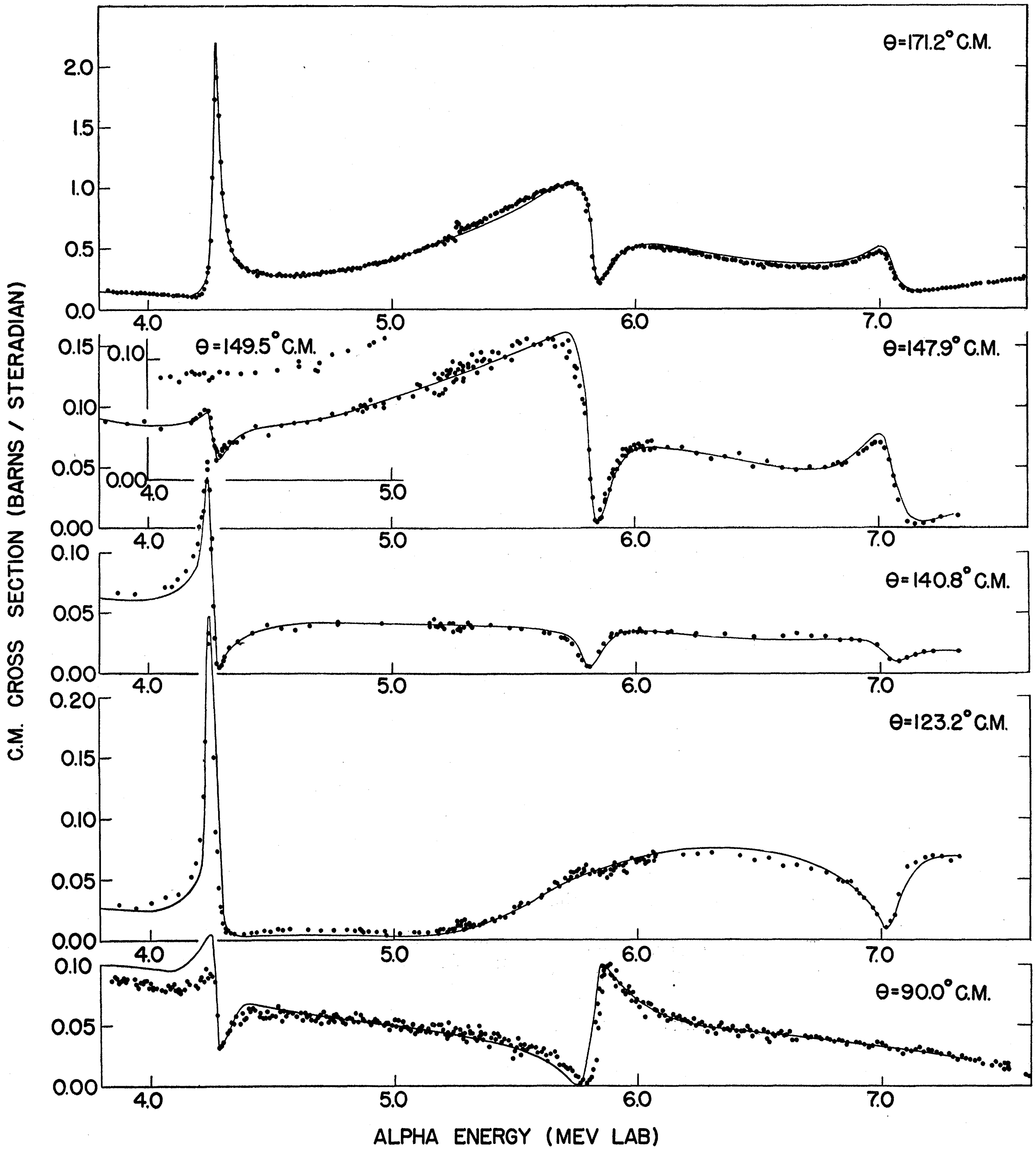

FIG. 1. Differential elastic scattering cross section of carbon for alpha paticles. The points are experimental data. The solid lines are a theoretical fit.

analyzer resulted in a spread of 6 to 11.4 kev about the central value. At the extreme back angle of 171.2° points were spaced at intervals of 8.5 kev for energies between 3.8 and 6.0 Mev, 11.4 kev from 6.0 to 6.6 Mev, and at 18-kev intervals above 6.6 Mev. At other angles points were taken less frequently except in regions where structure was expected because of the back-angle data.

III. DATA AND ANALYSIS

The points of Fig. 1 show the center-of-mass cross sections as a function of laboratory alpha-particle energy. For compactness the 171.2° cross sections are reduced in scale by a factor of ten relative to the others. Corrections have been applied for counter geometry and energy loss in the gas. No correction has been made for the one percent natural isotopic abundance of C^{13}

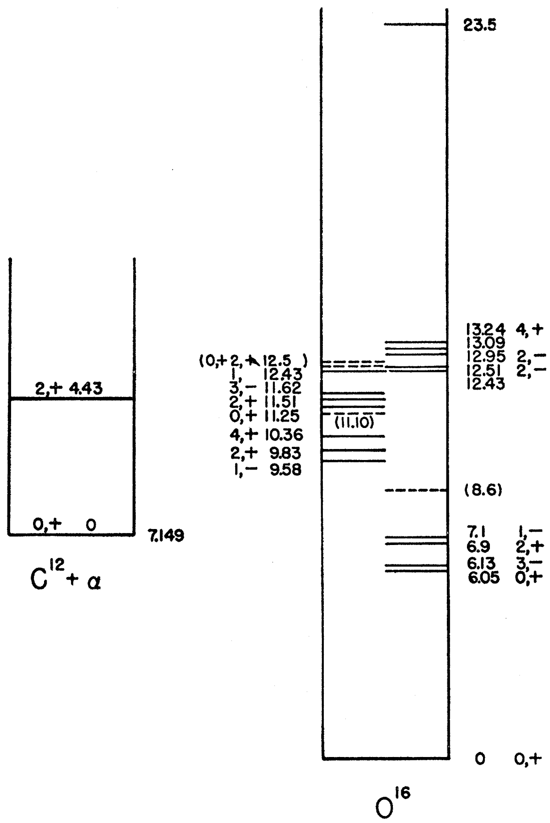

FIG. 2. Energy levels of O^{16}. Levels indicated by elastic scattering of alpha particles from carbon are shown at the left.

present in the propane target, since the scattering cross section is unknown. Statistical counting errors at 171.2° are less than 2 percent, but range up to 5 percent at other angles for energies where the cross section is low. Contribution from processes other than elastic scattering is negligible. Inelastic scattering to the 4.43-Mev level of C^{12} is possible only above 5.9-Mev lab energy. Even then the inelastic widths can be at most a few electron volts because of the small Coulomb barrier penetration probability for the degraded alpha particles.

In favorable cases inspection of the angular dependence of an anomaly in the scattering cross section permits immediate identification of the corresponding level in the compound nucleus; i.e., if resonance behavior is apparent at all angles except one, then the level must have the angular momentum and parity of the Legendre polynomial which vanishes at this angle. Such cases are the resonance at 4.28 Mev which vanishes only at 149.5° and is assigned $J=4$, $+$; the level at 5.82 Mev missing at 123.2° and hence $J=2$, $+$; and the $J=1$, $-$ level at 7.04 Mev identified by its absence at 90°.

However, the effect of any very broad level or of a $J=0$ level, which has a small effect at all angles, may be too subtle to be recognized so easily. A more complete analysis of phase shifts is then necessary even for qualitative assignment of the level parameters. Such an analysis was carried out by the graphical method which has been described in detail by Laubenstein[8] and others.

Sets of preliminary phase shifts for the partial waves up to $l=4$ were obtained which exactly fitted the cross-section data simultaneously at the five scattering angles. These phase shifts were then modified to follow single level dispersion formulas, taking into account the variation with energy of the Coulomb barrier penetration factor $1/A_l^2$ and the level shift

$$\Delta_\lambda = -\frac{\gamma_\lambda^2}{a}\left[\frac{d\ln A_l}{d\ln(kr)}+l\right] \qquad r=a.$$

These quantities may be calculated directly from tables of Coulomb wave functions,[9] once the hard-sphere scattering radius a has been fixed. Larger and smaller values were tried but Hill's[3] value of $a=5.43\times10^{-13}$ cm was found to be most satisfactory.

The single-level formulas then gave the reduced widths γ_λ^2 and the characteristic energies E_λ listed in Table I. The theoretical cross sections calculated from the single-level parameters of Table I are shown as solid lines on Fig. 1. The regions of misfit result from modifying the various preliminary phases to follow the single level formulas. It seemed that the exact fit which could be obtained everywhere without this stringent requirement could not be preserved, even by varying the parameter a.

Reseonance energies E_r of Table I indicate energies at which the phase differs from the hard sphere scattering phase by 90°. The O^{16} levels were obtained by adding the resonance energy in the center-of-mass system to 7.149 Mev, the binding energy of an alpha-particle in O^{16}. Reduced widths γ_λ^2 are given in the center-of-mass system and are compared with $\frac{3}{2}(\hbar^2/\mu a)$, the Wigner limit for single alpha-particle excitation.

The phase-shift analysis indicates three levels in addition to the "obvious" ones previously mentioned. The narrow resonance observed at 5.27 Mev in the 171.2° data remains unassigned because it is not clearly resolved at this angle nor does it appear at the other angles. Possibly it is to be associated with a nucleus

TABLE I. Summary of resonances.

J, Π	E_λ(lab) (Mev)	E_r(lab) (Mev)	Γ(lab) (kev)	γ_λ^2(c.m.) (Mev-cm)	O^{16*} (Mev)	Percent $\frac{3\hbar^2}{2\mu a}$
4, +	4.37	4.28	36	0.99×10^{-13}	10.36	26
(?)	···	5.27	10	···	11.10(?)	···
0, +	5.20	5.47	3300	3.0×10^{-13}	11.25	76
2, +	5.85	5.82	106	0.13×10^{-13}	11.51	3
3, −	6.82	5.96	1600	2.8×10^{-13}	11.62	73
1, −	7.07	7.04	230	0.17×10^{-13}	12.43	4

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other than O^{16}. Behavior of the $l=0$ and $l=2$ phases near the upper energy limit of this experiment suggests 0, + and 2, + levels in the vicinity of 12.5 Mev with widths greater than 100 kev. These are not listed in Table I because of the great uncertainty, but a 35° $l=2$ and nearly 90° $l=0$ resonant phase increase at 7.0 Mev has been used in calculating the theoretical cross sections of Fig. 1. Energies listed in Table I are thought to be correct within 20 kev, while errors in level widths are less than 10 percent, with the exception of the $l=0$ level, which is so broad that greater uncertainties are possible.

IV. CONCLUSION

Figure 2 is an energy level diagram for O^{16}. The levels indicated by this experiment and by Hill's are shown at the left. Levels previously reported are shown on the right. The broad 10.36, 11.25, and 11.62 levels may well be identified with single-particle excitation, although there is the possibility of a fortuitous overlap of wave functions for a number of particles which could cause such great widths.

The 10.36 $J=4$, + level is surely to be associated with the 4, + rotational level predicted by Dennison[10] from consideration of the alpha-particle model of the nucleus. In the accompanying paper Dennison[11] discusses in detail the remarkable agreement for O^{16} between the observed levels and those predicted by the alpha-particle model. Figure 3 shows the observed and theoretically predicted levels for comparison.

Additional levels occurring in the energy range covered by this experiment would not be found if they have even J values and odd parity or vice versa. Levels having experimental widths of less than 5 kev would also be undetected because of limitations in resolution.

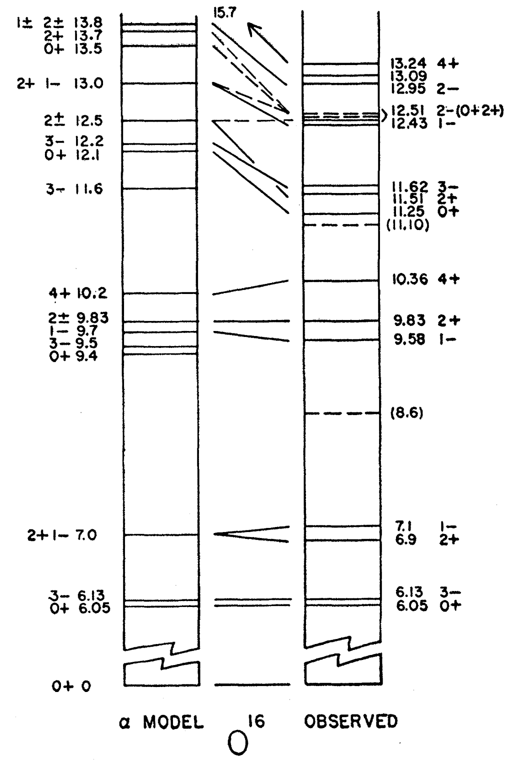

FIG. 3. Observed levels of O^{16} and levels obtained from alpha-particle model by Dennison. [Identification (a) of accompanying paper].

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