Proton-Oxygen Differential Scattering Cross Sections. II*

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(Received February 1, 1962)

The differential cross section for the elastic scattering of protons on O^{16} was measured for the laboratory energy range of 4.25 to 8.6 Mev. A differentially pumped gas scattering chamber with a CsI(Tl) scintillation detector was used. Measurements were made at the following center-of-mass scattering angles: 30° 2′, 54° 25′, 90° 0′, 103° 48′, 122° 57′, 140° 25′, 148° 50′, 166° 52′. Measurements were made at 0.0025- to 0.001-Mev intervals with a target thickness of 0.0025 to 0.001 Mev at 166° 52′. The other angles were measured at 0.001- to 0.040-Mev intervals with a 0.001- to 0.003-Mev target. The energy spread of the beam was probably less than 0.003 Mev for all the work. The uncertainties in the measured cross sections were approximately ±0.5%. Twenty-two resonances were found.

INTRODUCTION

ACCURATE high-resolution studies of the elastic scattering of protons by O^{16} are of interest for the detailed information they can yield concerning the compound nucleus F^{17}. The present paper II is a continuation of earlier measurements at Wisconsin I,[1,2] and covers the proton energy region from 4.25 to 8.6 Mev. Further data at Wisconsin in the energy range from 8.6 to 13 Mev are being prepared for publication and will include some inelastic cross sections.

A phase-shift analysis of the present work (and including some earlier data) is reported in an accompanying paper.[3]

Some recent work done by groups at Rice University,[4,5] by Kobayashi,[6] and by Sempert *et al.*,[7] overlaps part of the energy region reported here.

EXPERIMENTAL APPARATUS

A tandem Van de Graaff was used to provide a proton beam. The beam passed through three pumping impedances before entering the gas scattering chamber, as is shown in Fig. 1. On either end of this set of impedances a 1.5-mm-diam aperture was placed; the aperture system collimated the beam to a half-angle of 14′. The scattered protons were detected by a CsI(Tl) scintillator, which could be rotated about the incident beam direction at angles from 30°2′ to 166°52′ in the center-of-mass system. The unscattered beam passed through a 0.0025-mm Ni foil and was collected on a Faraday cup, discharging a capacitor which was initially at a known voltage. The null point was detected by a high-gain dc amplifier. Suppression of electrons produced by the beam passing through the Ni foil before entering the collector cup volume and of secondaries produced from impact of the beam on the Faraday cup, was achieved by an electrostatic suppressor. Tests indicated that 2500 v were sufficient for suppression. The chamber and associated equipment are discussed in more detail by Silverstein *et al.*[8] Minor changes which have been made later in the detector, vacuum systems, and pressure measuring device result in equal or improved performance. The collector cup was completely redesigned and placed external to the chamber in order to obtain a more nearly optimum geometry.

DATA REDUCTION

The scattering yield is reduced to a differential cross section in the center-of-mass system by the following expression[9,10]:

$$\frac{d\sigma}{d\Omega}=\frac{Y\sin\phi}{NnG}\left(\frac{\sin\phi}{\sin\theta}\right)^2\cos(\theta-\phi).$$

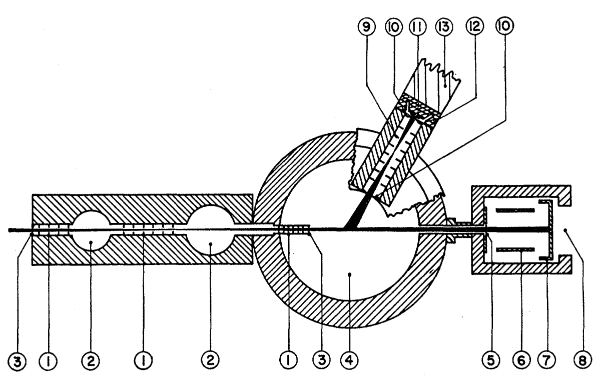

FIG. 1. Top view schematic of the scattering chamber. (1) Differential pumping impedances; (2) differential pumping port; (3) beam-defining aperture (1.5-mm i.d.); (4) gas volume; (5) collector cup foil (0.0025 mm thick); (6) suppressor electrode; (7) collector cup; (8) collector cup pumping port; (9) counter antiscattering baffles; (10) counter aperture; (11) CsI(Tl) scintillator; (12) Lucite light pipe; (13) photomultiplier (Dumont 6467).

* Work supported by the U. S. Atomic Energy Commission, and by the Graduate School from funds supplied by the Wisconsin Alumni Research Foundation.

[1] F. Eppling, Ph.D. thesis, University of Wisconsin, 1952 (unpublished).
[2] R. A. Laubenstein and M. J. W. Laubenstein, Phys. Rev. **84**, 18 (1951).
[3] S. R. Salisbury and H. T. Richards, following paper [Phys. Rev. **126**, 2147 (1962)].
[4] R. R. Henry, G. C. Phillips, C. W. Reich, and J. L. Russell, Bull. Am. Phys. Soc. **1**, 96 (1956).
[5] R. W. Harris, Rice University, (private communication).
[6] S. Kobayashi, J. Phys. Soc. Japan **15**, 1164 (1960).
[7] M. Sempert, H. Schneider, and M. Martin, Helv. Phys. Acta. **27**, 313 (1954).
[8] E. A. Silverstein, S. R. Salisbury, G. Hardie, and L. D. Oppliger, Phys. Rev. **124**, 868 (1961).
[9] G. Breit, H. M. Thaxton, and L. Eisenbud, Phys. Rev. **55**, 1018 (1939).
[10] H. A. Bethe, Revs. Modern Phys. **9**, 171 (1937).

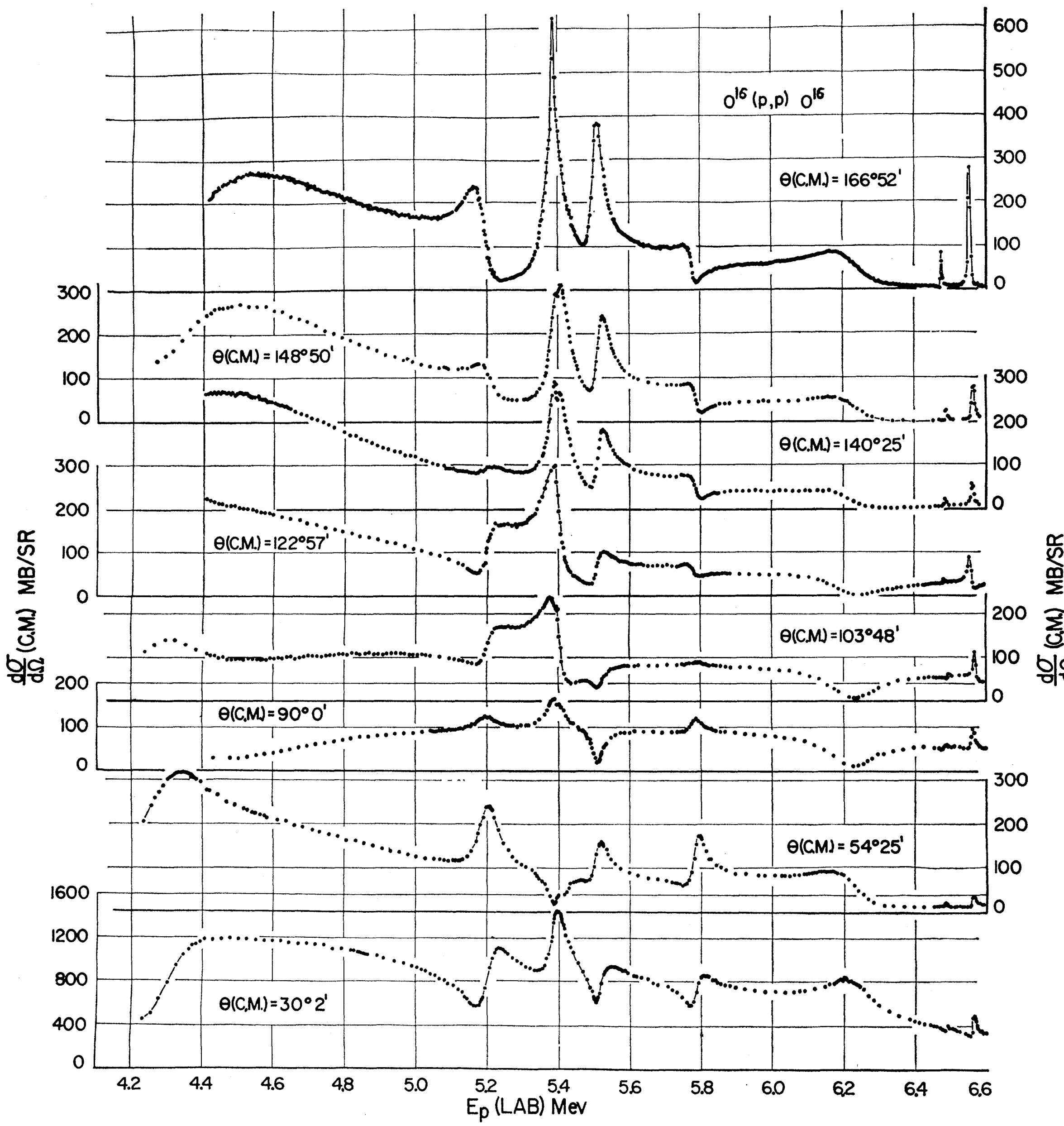

FIG. 2. Excitation curves from 4.25 to 6.6 Mev.

Y and N are the number of scattered and bombarding particles, respectively, n is the number of target nuclei per cm^3, and G is the geometric factor of the counter aperture system. ϕ and θ are the laboratory and center-of-mass scattering angles, respectively.

The uncertainty in Y, always less than 1%, is primarily the statistical one associated with taking a finite number of counts. Three scalers were used to measure and monitor the yield. The discriminators of two scalers were set at different values below the elastic peak while the third was set just above the elastic peak. The small difference in counting rate between the two lower scalers corresponded to an uncertainty of ± 0.05 mb/sr in the cross section.

The gas used was electrolytic oxygen.[11] A dry ice-acetone trap was used to remove the water vapor. The principal remaining impurity is expected to be O^{18} (0.2%) of O^{17} (0.04%). *Note added in proof.* Subsequent study of impurities in the oxygen shows ~0.2% H_2 and 0.2% N_2. Other quantities pertinent to the knowledge of the number of target nuclei per cc were: first,

[11] Electrolytic oxygen was obtained from General Dynamics Corporation, Liquid Carbonic Division, 707 Industrial Road, San Carlos, California.

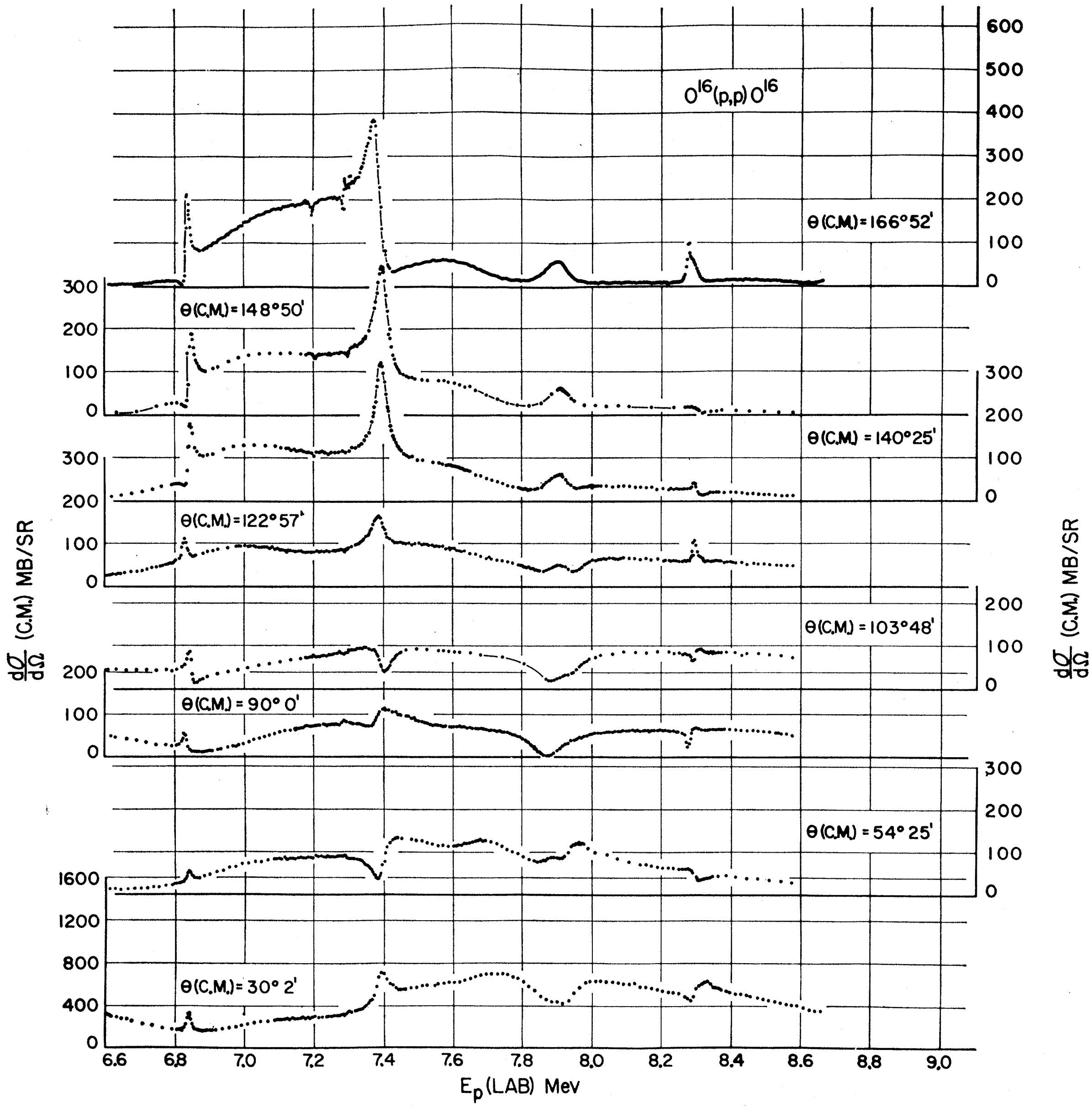

FIG. 3. Excitation curves from 6.6 to 8.6 Mev.

the density of the oil used for the monometer (known to within $\pm 0.05\%$); second, the uncertainty in measuring the difference in oil levels ($\pm 0.04\%$ for all except the back angle which was $\pm 0.28\%$); third, the temperature uncertainty for the gas ($\pm 0.07\%$).

The G factor was computed from the formulas derived by Silverstein[12] for the case of circular front and rear slits. The zeroth order corrections were made. Neglect of the higher order angular-dependent corrections produces an 0.5% error for the worst case, the $f_{7/2}$ level at $E_p = 5.4$ Mev,[3] and a much smaller error in all other situations. The uncertainty in measuring the slits and other parameters determining G resulted in an uncertainty of $\pm 0.2\%$.

The uncertainty of $\pm 0.15\%$ in the number of bombarding particles was primarily due to fluctuation of the null point as the capacitor was discharged. Other sources of this uncertainty, such as ionization current from residual gas in the collector cup, particles scattered outside the collector cup, and electrons knocked from the foil or secondaries from the cup, were investigated and found to be negligible. The uncertainty arising from the $\sin\theta$ factor is negligible for all angles except the largest, for which it is $\pm 0.4\%$.

[12] E. A. Silverstein, Nuclear Instr. and Methods 4, 53 (1959).

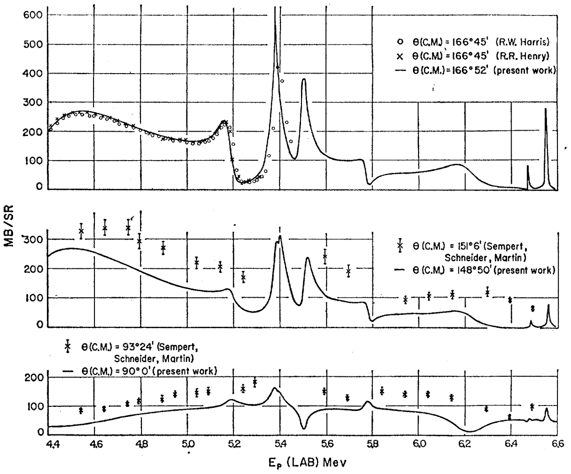

FIG. 4. Comparison of some of the present work with that done by Henry, Phillips, Reich, and Russel,[4] by Harris,[5] and by Sempert, Schneider, and Martin.[7]

The rms sum of the above uncertainties is then approximately $\pm 0.5\%$ for all angles except 166°52′ for which it is $\pm 0.7\%$. This sum does not include the statistical uncertainty in Y or possible uncertainties due to impurities in the gas (e.g., O^{17} and O^{18}).

The over-all accuracy of the experiment was checked by measuring differential cross sections for p-p scattering and for $O^{16}(p,p)O^{16}$. These were compared with previous work.[13,1] Data agreed within the combined uncertainties, which were $\pm 0.2\%$ for the original p-p data, $\pm 1\%$ for the original $O^{16}(p,p)O^{16}$ data, and $\pm 0.7\%$ for our data.

Other groups have calibrated the tandem Van de Graaff generator[14] such that the proton beam energy is known to within $\pm 0.1\%$. However, we have observed shifts of sharp resonances of up to ± 0.010 Mev from week to week. About half of this variation disappeared after the nuclear resonance probe was rigidly positioned in the 90° energy-analyzing magnet. The slits for the analyzing magnet were set at 2.54 mm (entrance) and 1.27 mm (exit) so the residual shifts could arise from different beam trajectories through the magnet.

From the width of some of the narrow resonances, it may be inferred that the energy spread in the beam was probably less than 0.003 Mev.

EXPERIMENTAL RESULTS

Differential cross sections were measured at eight angles, from 30°2′ to 166°52′ in the center-of-mass system, and from 4.25 to 8.60 Mev, incident proton lab energy.

The results are shown in Figs. 2 and 3. Statistical uncertainties are approximately the size of the points.

About 1500 data points were taken at 166°52′, which will henceforth be known as the "back angle," and 500 at each of the other angles.

The back-angle data were taken first at intervals of 0.0025 Mev, with a target less than or equal to 0.0025 Mev. The energy interval chosen is a compromise between the smallest possible steps consistent with our energy resolution (in order to detect narrow resonances) and the use of only a reasonable amount of machine time. Regions of rapidly varying cross section were later remeasured with steps as small as 0.001 Mev and a target thickness of less than 0.001 Mev.

Since the theoretical cross section expression contains Legendre polynomials as factors in the amplitude of the partial waves, resonant amplitudes will be maximum near 180°. For this reason data for an angle near 180° are taken first. We believe the back-angle data have located all resonances of elastic width greater than 0.001 Mev.

At the other angles then, steps as large as 0.040 Mev could be safely taken in regions of slowly varying cross section, while steps as small as 0.001 Mev were taken in regions of rapidly varying cross sections. The target thicknesses were less than 0.0025 Mev for all regions of narrow resonances, and at no time were more than 0.0035 Mev.

Except for the back angle, all angles were chosen to be near the zeros of the lower order Legendre polynomials. Zeros were chosen so the angles represented a fairly evenly spaced angular distribution. It was hoped that measurements at the zeros would help identify a resonant partial wave by the nature of its interference pattern. However at these higher energies, the nonresonant amplitudes are so complex that the interference pattern is not easily interpreted.

The data were corrected for energy loss in the gas before reaching the target. The correction was deter-

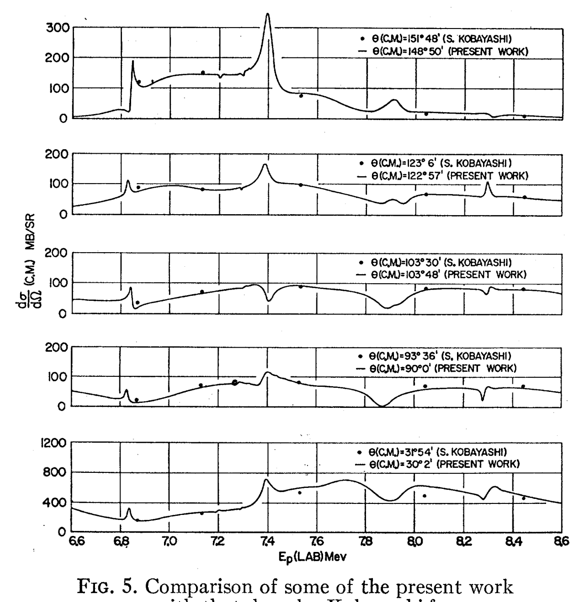

FIG. 5. Comparison of some of the present work with that done by Kobayashi.[6]

[13] H. R. Worthington, J. N. McGruer, and D. E. Findley, Phys. Rev. **90**, 899 (1953).

[14] P. Dagley, W. Haeberli, and J. X. Saladin, Nuclear Phys. **24**, 353 (1961).

mined by measuring the peak energy of three narrow resonances which lay in the range 3.5 to 8.2 Mev as a function of gas pressure. These peak energies were then extrapolated to zero pressure. The correction varied from 0.018 to 0.003 Mev.

Comparison with the most recent Rice University data[5] indicates a systematic cross-section difference of about 5% with our work. The original data taken by Henry fit our data slightly better than the later data taken at Rice. Figure 4 shows this comparison at the respective back angles. The Rice data are plotted as circles and crosses and our data as a solid line. Rice data do not show the narrow satellite level at 5.402 Mev which has been identified as $s_{\frac{1}{2}}$.[3]

Work done by Sempert, Schneider, and Martin[7] is compared to ours at the two nearly equal angles. The agreement is not good. Their results are consistently high an amount several times their quoted uncertainty of $\pm 10\%$. The comparison is shown in Fig. 4.

Kobayashi's work[6] is compared to ours in the cases for which we have data at comparable angles. See Fig. 5. Agreement is excellent, cross sections usually agreeing within the combined experimental uncertainties. Kobayashi estimates his uncertainty as a few millibarns, and ours is about $\pm 0.5\%$. The experimental resolution is much poorer for Kobayashi's work than for ours so his data would be expected to agree with ours only in regions of slowly varying cross section.

PHYSICAL REVIEW VOLUME 126, NUMBER 6 JUNE 15, 1962

F^{17} Level Parameters*

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(Received February 1, 1962)

$O^{16}(p,p)O^{16}$ differential cross-section data for $E_p=2-7.6$ Mev have been used to fix parameters of F^{17} levels. The cross-section data were first fitted to a partial-wave phase-shift expansion by a least-squares method using an IBM 704. The level parameters were then obtained by application of dispersion formalism to the extracted phase shifts. The two-level approximation was used where appropriate. Four very narrow levels and the well-known $7/2^-$ level at $E_p=3.47$ Mev were ignored in the present analysis. However, resonant energies and limits on widths (obtained by inspection) for these and higher energy F^{17} states are given. Level schemes of O^{17} and F^{17} are compared. Assignment of levels to particular nuclear configurations is attempted. An appendix is included, giving illustrations of branching solutions in the phase-shift analysis.

INTRODUCTION

SUCCESSFUL analysis of $O^{16}(p,p)O^{16}$ data will fix level parameters in the compound nucleus F^{17}. Differential cross sections for this interaction in the proton energy range from 4.25 to 8.6 Mev are reported in the preceeding paper.[1] These cross sections are used for the phase-shift analysis in the range $E_p=4.25-7.6$ Mev. Data taken by Eppling[2] at Wisconsin, and by groups at Rice University[3,4] are here used for a similar analysis in the range $E_p=2.0-4.25$ Mev.

Dispersion formalism permits the reproduction of each resonant phase shift by a set of level parameters. The present analysis stops with the extraction of such level parameters. A logical further step would be the generation of these level parameters by a simple nuclear model.

* Work supported by the U. S. Atomic Energy Commission, and by the Graduate School from funds supplied by the Wisconsin Alumni Research Foundation.

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[1] S. Salisbury, G. Hardie, L. Oppliger, and R. Dangle, preceding paper [Phys. Rev. **126**, 2143 (1962)].

[2] F. Eppling, Ph.D. thesis, University of Wisconsin, 1952 (unpublished).

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[4] R. R. Henry, G. C. Phillips, C. W. Reich, and J. L. Russell, Bull. Am. Phys. Soc. **1**, 96 (1956).

THE PHASE-SHIFT ANALYSIS

The partial wave expansion takes the following form for the case of spin-$\frac{1}{2}$ particles on spin-zero particles.[5,6] (The notation follows reference 6.)

$$d\sigma/d\Omega(\text{c.m.}) = (1/k^2)(|A|^2+|B|^2),$$

where

$$A=-\tfrac{1}{2}\eta \csc^2(\theta/2) \exp i\eta \ln[\csc^2(\theta/2)] +\textstyle\sum_l (l+1)P_l(\cos\theta) \sin\delta_l^+ \exp i(\alpha_l+\delta_l^+) +\sum_l lP_l(\cos\theta) \sin\delta_l^- \exp i(\alpha_l+\delta_l^-),$$

$$B=\sin\theta \sum_l \frac{dP_l(\cos\theta)}{d\cos\theta}[\sin\delta_l^- \exp i(\alpha_l+\delta_l^-) -\sin\delta_l^+ \exp i(\alpha_l+\delta_l^+)].$$

The preceding expression is valid if the elastic scattering channel is the only open channel. If one neglects the small (p,γ) widths, then up to $E_p=5.55$ Mev only the elastic scattering channel is open. At $E_p=5.55$ Mev, the $O^{16}(p,\alpha)N^{13}$ channel opens. At $E_p=6.3$ Mev, the $O^{16}(p,p')O^{16*}$ channel opens. If these

[5] C. L. Critchfield and D. C. Dodder, Phys. Rev. **76**, 602 (1949).

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