and

$$\Delta = a_0^{-2} + B^2 \simeq a_0^{-2}[1+(\hbar v/2e^2)^2(1+y)] + O(m/M),$$

where

$$y = [2A'AM\theta/(A'm+Am)]^2 = (\theta/\theta_0)^2.$$

We note that $I_{BK} \sim \Delta^{-3}$ [see Eq. (I.3) and Eq. (16)], so that the differential cross section, Eq. (9), is proportional to Δ^{-2} and higher reciprocal powers of Δ. Consequently, the angular distribution is largely confined to angles less θ_0, as discussed in Sec. 3.

When the integral I_0' is combined with I_{BK} in Eq. (9) and integrated over angles, the resulting total cross section can be expressed in the form of Eq. (17). For arbitrary Z' and Z and/or captures into excited states the general procedure is the same. However the algebraic complexity grows enormously, and it is advantageous in some instances to evaluate certain expressions (such as the integrals λ_n) numerically rather than analytically.

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The $C^{12}(p,p)C^{12}$ Differential Cross Section*

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The $C^{12}(p,p)C^{12}$ differential cross section has been observed at four scattering angles by using differentially pumped gas targets of propane and ethylene. The scattering angles employed were 106.4, 127.8, 148.9, and 169.2 degrees in the center-of-mass system, and the energy range covered extended from 0.4 to 4.3 Mev. These measurements show the angular behavior of the previously discovered scattering anomalies at 0.46 and 1.7 Mev and give values of the absolute cross section accurate to within five percent. A careful search in three- and six-kev steps failed to reveal any indication of any hitherto unknown scattering resonances within the energy range surveyed.

I. INTRODUCTION

IN a previous article[1] we reported the results of a partial wave analysis of the differential cross section for elastically scattered protons from ordinary carbon obtained by Goldhaber and Williamson.[2] Although that analysis yielded definite values for the momenta and parities of the excited states of N^{13}, it also led to values of the resonant energies and widths which differed somewhat from those obtained from the proton capture data.[3] In addition, the experimental and calculated scattering cross sections could not be brought into agreement below one Mev. In the hope of removing these discrepancies, we have measured the $C^{12}(p,p)C^{12}$ differential cross section with increased accuracy at four scattering angles and have analyzed the new data by the same method. This paper describes the experiment and presents the data obtained. The following paper will deal with the analysis.

II. APPARATUS

Unless the absolute value of the scattering cross section is known to within a few percent, the phase shift analysis is extremely difficult and the results uncertain. In view of this fact, one of the major considerations in planning the experiment was the type of target to be used and the technique for measuring its thickness. Solid targets of the required purity and uniformity of thickness are difficult to prepare and are liable to additional carbon deposition during bombardment. The final decision was to employ a gas target, since its thickness depends only upon the dimensions of the counter slit system, the scattering angle, and the pressure and temperature of the scattering gas. All these quantities are readily measurable to a degree of accuracy somewhat higher than required for the projected experiment.

The gas actually used for most of the experiment was propane, although ethylene was used for some of the data at low bombarding energies, because it gives rise to less small angle scattering than propane at the same pressure. Being compounds of hydrogen and carbon only, these gases behave like pure carbon targets at scattering angles greater than 90 degrees. They have the further advantage of giving satisfactorily high yields of scattered protons at feasible chamber pressures and incident beam intensities.

Figure 1 is a cross-sectional view of the apparatus as seen from above. Its four principal components are the differential pumping column A, the scattering chamber B, the collector cup assembly C, and the two proportional counters together with their collimating slit systems D and D'. In operation the incident beam from

* Work supported by the AEC and the Wisconsin Alumni Research Foundation.
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[1] H. L. Jackson and A. I. Galonsky, Phys. Rev. 84, 401 (1951).
[2] G. Goldhaber and R. M. Williamson, Phys. Rev. 82, 495 (1951).
[3] W. A. Fowler and C. C. Lauritsen, Phys. Rev. 76, 314 (1949); D. M. Van Patter, Phys. Rev. 76, 1264 (1949); and J. D. Seagrave, Phys. Rev. 84, 1219 (1951).

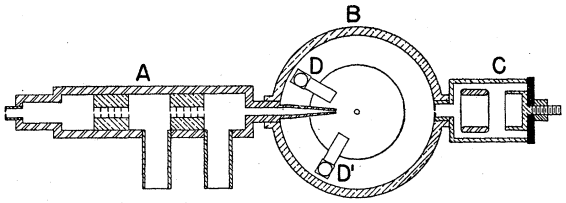

FIG. 1. Cross-sectional view of the scattering chamber as seen from above. The differential pumping column A isolates the scattering chamber from the electrostatic analyzer and collimates the incident beam. It consists of three stages, each separated from the adjoining ones by small circular apertures. The scattering chamber B is a bronze casting with an inside diameter of nine inches and a depth of two and one-half inches. The collector cup housing C incloses the collector cup and a ring magnet to suppress secondary electrons. The magnet is mounted on Lucite supports and is also used as an electrostatic suppressor electrode. A 0.00002-in. nickel foil prevents the gas in the chamber from entering the collector cup housing. The two proportional counters D and D', together with their collimating slit systems, are mounted on a turntable which can be rotated from the outside.

the proton accelerator, after passing through the electrostatic analyzer, enters the differential pumping column where it is collimated. It crosses the scattering chamber and is finally stopped by the collector cup. In the meantime those protons which have been scattered from the incident beam and whose trajectories pass through the counter slit systems enter the counters and are recorded. The collector cup is connected to a current integrator which shuts off the counter recording circuits as soon as a predetermined charge (10 microcoulombs) has been collected.

The differential pumping column prevents the target gas in the chamber from entering the electrostatic analyzer. It is superior to a thin foil for several reasons. First, the scattering chamber undergoes continuous flushing so that contaminant gases and vapors do not accumulate. Second, the problem of energy degradation and straggling of the incident beam, which would occur both in a foil and in the carbon deposits, which would gradually build up on it, does not arise. Third, the small angle scattering which a foil would introduce into the beam, especially at low energies, is absent. The deleterious effects of the gas within the column are negligible, since the column pressures are far less than that in the chamber itself. As is clear from the figure, the differential pumping column consists of three pressure dropping stages. A fast forepump (5 liters/second capacity) exhausts each of the first two sections, and an oil diffusion pump (250 liters/sec capacity) the last.

The aperture at each end of the column is a 1.5-mm hole drilled in a 0.003-inch stainless steel disk. In addition to restricting the gas flow, these apertures collimate the incident beam. As they are about 43 cm apart, the maximum half-angle spread in the incident beam, when it enters the chamber, is approximately 12 min. Each of the two intermediate capillaries consists of twenty-two stainless steel apertures, each of which is 2.0 mm in diameter and 0.003 inches thick. All apertures, including the ones at the ends, were electropolished until they were free from irregularities under microscopic examination. When the pressure in the scattering chamber is 10 mm Hg, the flow rate through the column is from 10 to 15 liters STP per hour, and the pressures in the successive stages are roughly 0.5, 10^{-2}, and 10^{-5} mm Hg, respectively.

The scattering chamber used in the present experiment is similar in design to the one described by Herb, Kerst, Parkinson, and Plain.[4] It is a bronze casting with an inside diameter of 9 in. and a depth of $2\frac{1}{2}$ in. A turntable, rotatable from the outside and situated just above the chamber floor, supports the proportional counters and their slit systems. The degree marks on the rim of the turntable together with a vernier index secured to the floor of the chamber, enable the operator to read the scattering angle to 0.1 degree.

The design of the collector cup assembly is conventional. An alnico ring magnet, $2\frac{1}{2}$ in. inside diameter with a uniform transverse field of about 300 gauss, rests on Lucite supports and is connected to an external electrode so that it can be used to provide electrostatic as well as magnetic suppression of secondary electrons. A 0.00002-inch nickel foil prevents the target gas from entering the collector cup housing which is kept evacuated to about 5×10^{-6} mm Hg.

Each of the two proportional counters used consisted of an inconel tube $1\frac{3}{4}$ in. long and $\frac{5}{8}$ in. inside diameter, with a 0.005-in. Kovar wire suspended along the center axis. Since propane and ethylene are good counting gases, it was thought advantageous to avoid the complication of a separate counter filling system by letting the counters operate with the same gas and at the same pressure as the chamber itself. Because the proton entrance slots were necessarily rather large, they had to be covered with a thin metal foil (0.00002-in. nickel) to prevent the electric field from extending outside the counter volume. A small separate opening was provided for the gas inflow. In practice, the open style counters proved to be difficult to adjust and the range of pressures suitable both for satisfactory counting and for accurate current integration was inconveniently narrow, especially at low energy. Below 0.6 Mev the open style counters had to be abandoned because the usable pressure range disappeared altogether. In order to cover the lower scattering anomaly, we sealed the counters and provided them with a separate filling system.

The sensitive volume of the scattering chamber and the solid angle subtended by the counter are determined by two rectangular slits, 2.0×9.0 mm placed $1\frac{3}{4}$-in. apart. The slit edges are made from stellite ground to 0.0001-inch tolerance. Two slightly larger sets of auxiliary slits stand between the two defining slits to prevent protons scattered from the slit support blocks from entering the counter. Figure 2 shows the details of the counter slit system assemblies.

[4] Herb, Kerst, Parkinson, and Plain, Phys. Rev. **55**, 998 (1939).

The recording circuits connected to each counter include a pre-amplifier, amplifier, and two discriminator-scalers operating in parallel. In operation the two discriminators were set at substantially different minimum pulse height acceptance voltages so as to monitor the number of pulses outside the main proton group.

A glass arm manometer filled with Octoil-S measured the chamber pressure. One arm was connected directly to the chamber and the other to the collector cup diffusion pump. The cathetometer built by Findley, McGruer, and Worthington[5] was used to observe the displacement of the oil menisci.

The propane vapor from the bottle was admitted into the chamber through a long-taper needle valve. In order to stabilize the vapor pressure of the liquified propane in the bottle, we immersed it in a bath of crushed ice and water. The sections of tubing between the bottle and the chamber were quite long in order to bring the vapor up to room temperature before it entered the chamber.

The pressure stability was quite good. The principal variation was that caused by the "pumping" action of the proton beam. This effect is an increase of pressure that occurs when the intensity of the incident beam is increased. The change of pressure associated with a change of beam current from zero to the maximum attainable value was roughly 0.1 to 0.2 mm Hg, the exact amount varying somewhat with the chamber pressure and the energy of the beam. The seriousness of the effect was minimized by keeping the beam as steady as possible and by continuously monitoring the pressure. To accomplish this, a team of three worked together in taking data; one member controlled the proton accelerator and the electrostatic analyzer, one recorded counter data, and the third observed the chamber pressure and recorded as many values per run as time permitted.

III. EXPERIMENTAL RESULTS

In the present experiment we measured the $C^{12}(p,p)C^{12}$ differential cross section from 0.4 to 4.3 Mev at four different scattering angles. Figure 3 shows the results obtained. In order to simplify the subsequent analysis as much as possible, we calculated the scattering angle and the absolute value of the cross section in the center-of-mass system but left the energy of the incident beam in the laboratory system. At two angles, 169.2 and 106.4 degrees, observations were made every three kev up to two Mev, and every six kev thereafter in an effort to locate any narrow resonances hitherto undiscovered. The results show no evidence whatever of any additional levels in the energy range surveyed. Except over the region of the 1.7-Mev anomaly, only about one-fifth of the total number of points recorded at these angles appear in the figure.

[5] Findley, McGruer, Worthington, Phys. Rev. (to be published).

The counters were sealed and pressurized to obtain data between 0.4 and 0.6 Mev. As the counter design included no provision for eventual sealing, the task of attaching foils to the proton entrance slots, securely enough to withstand the required internal pressure, was most difficult. After many trials, we successfully sealed one counter with a 0.00002-in. nickel foil, but never succeeded with the other. We finally covered the second counter slot with a 0.00005-in. nickel foil instead. In operation over the energy region of the lower scattering anomaly, the latter foil introduced so much straggling into the energy of the protons entering the counter that the voltage spread of the proton pulses was unacceptably broad. Consequently, the data from this counter had to be rejected and, for lack of time, we did not cover the two lower scattering angles with the usable counter.

The cross section at 169.2 degrees is quite similar to that obtained earlier at 164 degrees from a solid target,[2] except that its absolute value in the vicinity of the 0.46-Mev anomaly is about 20 percent larger. Thus, the serious discrepancy in the low energy region between the original data and the analysis based on it[1] is resolved. The crucial point of interest in the 169.2-degree data is the unmistakable presence of two maxima and minima near 1.7 Mev. Their existence is good evidence that the scattering anomaly at this energy is not the result of a single narrow energy level.

IV. DISCUSSION OF ERRORS

Most of the points in the present data are based on more than ten thousand counts and all on more than

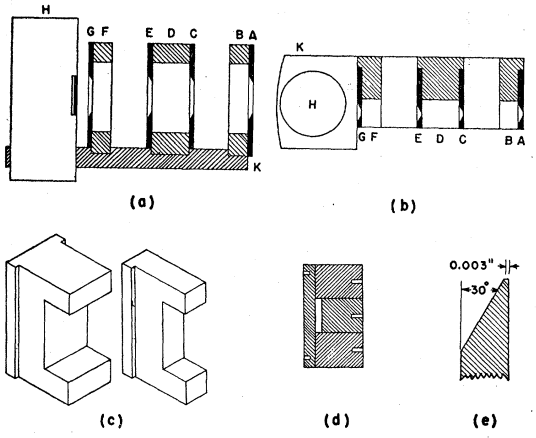

FIG. 2. Drawings *a* and *b* are cross-sectional views of the counter and slit system assembly as seen from the side and from above, respectively. *A* and *G* are the slits which define the solid angle subtended by the counter; *C* and *E* are auxiliary slits whose function is to prevent multiply scattered protons from reaching the counter; *B*, *D*, and *F* are the slit support blocks; *K* is the slit assembly base plate; and *H* is the proportional counter. Drawing *c* shows the shape of the slit support blocks. Drawing *d* shows the shapes of the stellite plates forming the slit and their arrangement on the face of the support block. Drawing *e* is a cross-sectional view of the slit forming edge of the stellite plates.

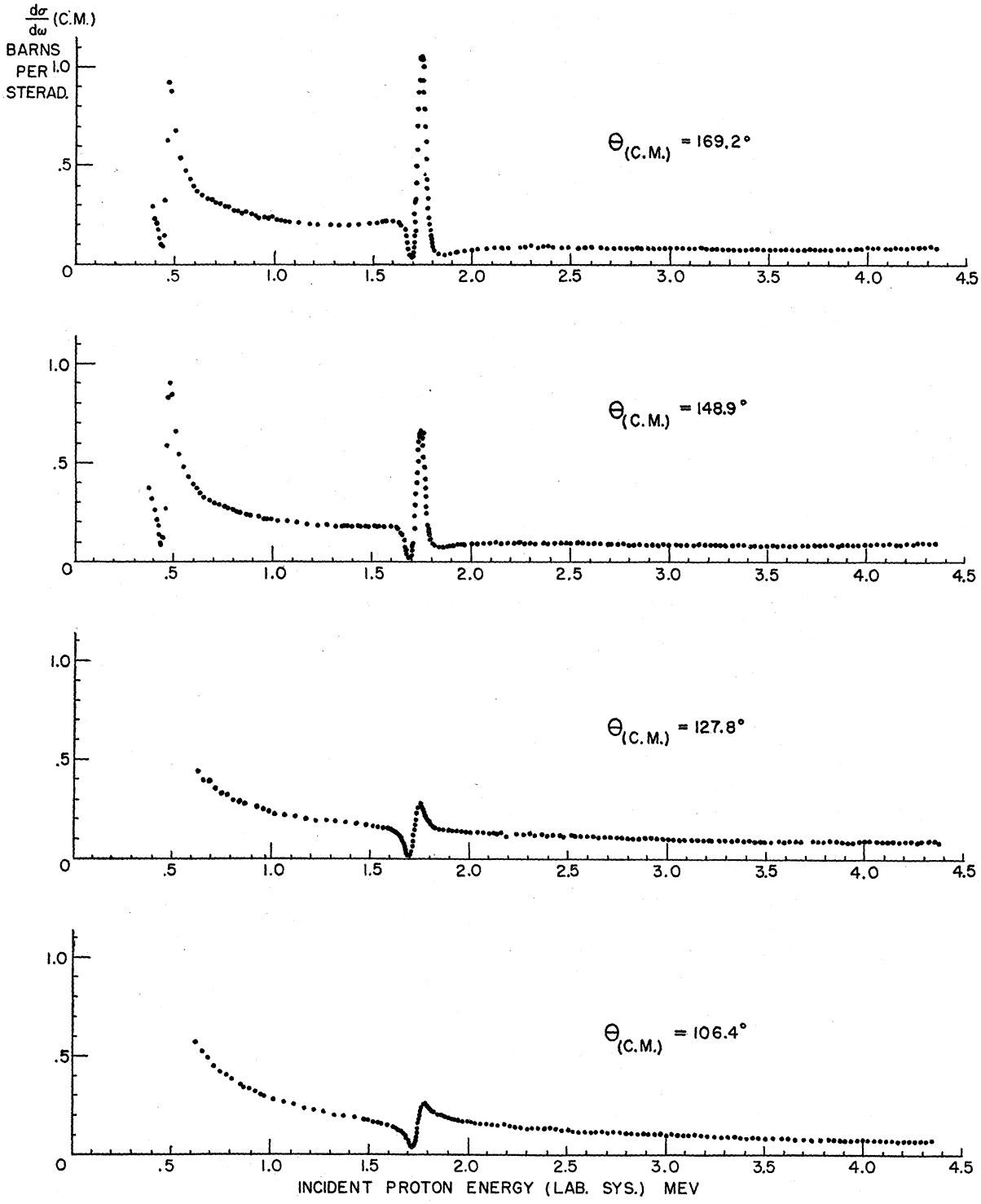

FIG. 3. The $C^{12}(p,p)C^{12}$ differential cross section. The values of the cross section and of the scattering angles are given in the center-of-mass system, while the bombarding energy is given in the laboratory system. At 106.4 and 169.2 degrees, observations were made every three kev up to two Mev and every six kev thereafter in an effort to locate any unknown scattering anomalies. However, except over the resonance at 1.7 Mev, only about one-fifth of these points are plotted. The 0.46-Mev scattering anomaly does not appear at the two smaller scattering angles because the data at these angles below 0.6 Mev were defective.

twenty-five hundred. Therefore, the statistical uncertainty is usually less than one percent and never more than two percent.

Three important sources of error that can affect the accuracy of current integration are the failure of an appreciable fraction of the incident beam to reach the collector cup, failure to suppress secondary electrons, and deficiencies in the current integration circuit. As we used the current integrator built by Findley *et al.*,[5] for the recently completed proton-proton scattering experiment, the errors from the last-mentioned cause should be negligible since the circuit was designed to be accurate to one part in ten thousand.

The effect of unsuppressed secondary electrons was investigated by plotting yield *versus* suppressor voltage curves at constant incident proton energy and target gas pressure. These curves indicated complete suppression within statistics at sixty volts, but as an additional precaution we used a bias of 300 volts while taking data.

The failure of a fraction of the beam to reach the collector cup because of small angle scattering was fairly troublesome, especially at low energies with the open style counters. To check the seriousness of this effect, we plotted numerous yield/pressure *versus* pressure curves below 1.5 Mev. We accepted yield data in any given energy region only when the appropriate curve of Y/P *versus* P was horizontal up to pressures 1.5 to 2.0 times the pressure used to obtain data for cross-section calculation. In the 0.6- to 1.0-Mev region, small angle scattering in propane was excessive at the minimum usable pressure with the open style counters. In this region, therefore, ethylene was used instead. During sealed counter operation, the effect was reduced to a tolerable level by using a chamber pressure of about 3 mm Hg. The error in the current integration therefore lies within the statistics of the Y/P curves, or about one percent.

No direct means of testing the efficiency of the open style counters was available. However, there are many regions of overlap in the data where yields were obtained for a wide range of gas pressure and counter voltage. Since these regions show no discrepancies greater than statistics, it is plausible to assume that the counters are reliable to within statistics or one percent.

The propane used has an advertised purity of 99.9 percent. No analysis was made to check the supplier's[6] claim. On the assumption that the impurities present are mostly light hydrocarbons, the resulting error would be negligible. The purity of the ethylene used is unknown, but in the regions where ethylene and propane data overlap, no discernable discrepancy exists.

As stated earlier, the target thickness depends upon the gas pressure and temperature, the dimensions of the counter slit systems, and the scattering angle. The combined error of the pressure, temperature, and slit dimension measurements should not exceed 0.1 percent, but an error of 0.1 degree in the scattering angle introduces an error of one percent into the value of the absolute cross section at 169.2 degrees. The error introduced at the smaller scattering angles is, of course, somewhat less.

Ordinary carbon is about 99 percent C^{12} and one percent C^{13}. Since the differential cross section for elastically scattered protons from C^{13} has not been measured, the error introduced by the isotopic contamination at any given energy and scattering angle cannot be estimated.

The errors cited are those which affect the magnitude of the cross section at a given energy and scattering angle. The sum of these errors is about 5 percent plus whatever error the presence of C^{13} introduces. Of the errors mentioned, that in the scattering angle affects only the absolute cross section, while the others may or may not affect the relative cross section as well, depending upon whether they are or are not functions of time and/or energy. The sum of the errors that may affect the relative cross section is therefore about four percent plus the C^{13} effect.

Under the conditions of the experiment, the error in the absolute value of the energy of the incident beam is not greater than 0.2 percent. An additional source of error arises in correcting for the stopping power of the gas between the last analyzer slit and the sensitive volume of the scattering chamber. The magnitude of the limit of this error is hard to estimate, but it is believed that it could hardly exceed 2 kev in the worst case.

[6] Matheson Company, East Rutherford, New Jersey.