THE

PHYSICAL REVIEW

*A journal of experimental and theoretical physics established by E. L. Nichols in 1893*

SECOND SERIES, VOL. 76, NO. 11 DECEMBER 1, 1949

# Magnetic Analysis of the $C^{12}(d,p)C^{13}$ and $O^{16}(d,p)O^{17}$ Reactions

W. W. BUECHNER, E. N. STRAIT, A. SPERDUTO, AND R. MALM
*Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts*

(Received July 29, 1949)

The proton groups that result from the deuteron bombardment of $C^{12}$ and $O^{16}$ targets have been analyzed with a high resolution magnetic spectrometer. For the $C^{12}(d,p)C^{13, 13*}$ reactions, the $Q$-values have been measured as 2.729±0.009 and −0.370±0.003 Mev. No evidence has been found for energy levels of lower energy than the one which is thus determined to be at 3.098±0.008. The reaction energies for the two proton groups observed to come from $O^{16}(d,p)O^{17}$ are 1.925±0.008 and 1.049±0.007 Mev, with 0.876±0.009 Mev as the energy of the first excited state in $O^{17}$.

## I. INTRODUCTION

THE various proton groups that result from the deuteron bombardment of $C^{12}$ and $O^{16}$ have been studied in many different ways since the early work of Cockcroft and his collaborators. Knowledge of the energy released from these reactions provides information regarding the masses and the low lying energy levels of the residual nuclei, $C^{13}$ and $O^{17}$. The energy levels of $C^{13}$ are of particular interest, since their location can be compared with the levels of $N^{13}$ which have been determined by other methods. Such a comparison affords a partial check on certain current ideas regarding the structure of light nuclei.

In the present work, the energies of the protons emitted at 90 degrees to the incident deuteron beam have been determined with a high resolution, 180-degree analyzing magnet. In general, the carbon and oxygen targets were the very thin layers of surface contaminants that experience has shown to be present on nearly all targets operated at red heat in a system evacuated by mercury pumps and provided with liquid-air traps. The presence of such very thin layers is not usually a disadvantage, however, since a precise determination of the energy of the groups that originate in them may make it possible to employ them as convenient secondary energy standards.

## II. APPARATUS AND EXPERIMENTAL ARRANGEMENT

The apparatus and the experimental technique are essentially the same as those described[1] in connection with some measurements on the 480-kev level of $Li^7$. Deuterons from an electrostatic accelerator are analyzed by a 90-degree deflecting magnet, and the resultant atomic beam is directed at a target located between the pole faces of an annular magnet. The particles emitted at right angles to this beam are deflected through 180 degrees by the annular magnet and are detected on nuclear-track plates placed in the focal plane.

In the present experiment, it is essential that the field strength in the annular analyzing magnet be accurately determined over a wide range. For this purpose, the flip-coil flux meter, previously described, has been replaced by a system that has proved very reliable and convenient. A small rectangular coil placed between the pole faces of the magnet is fastened to an arm that is rigidly mounted at the center of the beam of an analytical balance of 0.1 mg sensitivity. The balance is adjusted so that, with no current through the coil and no weight on the balance pan, the system is in equilibrium when the coil is parallel to the lines of force. In use, the coil current required to balance a standard two-gram weight placed on one of the balance pans is used as a measure of the magnetic field. A mirror mounted on the balance arm serves to reflect the image of an incandescent filament onto a scale on the laboratory wall, thus providing a convenient method of determining the balance position.

For the range of field strengths employed in these experiments, the coil current required for balance is between 20 and 50 milliamperes. This current is measured with a type K potentiometer. Careful measure-

[1] Buechner, Strait, Stergiopoulos, and Sperduto, Phys. Rev. **74**, 1569 (1948).

TABLE I. Calculation of errors for reaction energy for $C^{12}(d,p)C^{13}$.

| Source of error | Magnitude of error |
|---|---|
| Fundamental constants and $H\rho$ for polonium $\alpha$-particles | $\pm 4.5$ kev |
| Spread of beam at entrance slit | $\pm 0.1$ |
| Angle of observation (deviation from 90 degrees) | $\pm 2.5$ |
| Non-uniformity of magnetic field at target and detector | $\pm 0.1$ |
| Diameter of magnet | $\pm 0.6$ |
| Homogeneity of field | Negligible |
| Measurement of field | $\pm 6.9$ |
| Determination of peak location | $\pm 1.7$ |
| Net probable error | $\pm 9$ kev |

ments have been made over a wide range of field strengths on the relationship between the coil current and the corresponding balancing weight. This relationship has been found to be accurately linear even for very small field strengths. As in our previous work, this flux meter is calibrated in terms of the magnetic field required to produce a measured deflection of alpha-particles from polonium. A value of $3.3158\times10^5$ gauss-centimeters for these particles[2] has been used throughout. This flux meter has been in use for approximately one year and has been frequently recalibrated, the individual calibrations being consistent to within 0.1 percent.

The nuclear-track plates used as detectors are exposed at different magnetic field strengths, and thus each records an interval in the energy spectrum of the particles being studied. In order to make possible the accurate determination of the positions on the plates of the peaks observed, the plates are counted in strips 0.1 mm in width. With both the alpha-particles used for calibration and the groups from the reactions, sufficient exposure is given so that there are several hundred tracks in each strip in the region of the peak maximum. Figure 1 is a plot of data obtained in this way for the polonium alpha-particles. The plate from which this curve was obtained was counted with a magnification of 720. Similar curves have been obtained for the various particle groups studied.

Two types of targets have been employed in these experiments. As has been mentioned, experience has shown that a very thin film containing both oxygen and carbon exists upon the surface of all target materials unless extreme precautions are taken. In general, the thickness of these films appears to be less than 5 kilovolts, as determined from the width of the proton peaks that appear as a result of the bombardment. In such cases, this half-width of the proton groups is mainly determined by the width of the slit through which the incident beam is admitted to the target chamber for the annular magnet.

A search for low energy protons from such targets is complicated by the presence of deuterons that have been elastically scattered from the solid material upon which the films have been deposited. To facilitate the counting of the proton tracks in the presence of the heavy background caused by these scattered deuterons, thin aluminum foils have been placed immediately in front of the emulsion surface. These foils are of such a thickness as to stop completely these scattered deuterons. This inconvenience due to the scattering from a solid target may be eliminated by the use of targets of thin carbon- and oxygen-containing organic films, such as Formvar, which are supported by an open-wire framework that is not in the path of the incident beam. With such thin targets, the plates are very free of any background caused by scattering. Such targets tend to disintegrate under prolonged bombardment, however, and frequent replacements are necessary.

The energy of the incident deuteron beam employed in each series of measurements has been determined from measurements of the deflection of elastically scattered deuterons. In this case, it is desirable that the deuterons be scattered from a very thin target. Gold-leaf targets and targets that consist of a thin layer of platinum evaporated onto a copper backing have been used. The latter targets have been very satisfactory and are much more rugged than are the gold-leaf targets. The resolution of the apparatus is sufficient to separate completely the deuterons scattered by the platinum from those scattered by the copper backing. Where the Formvar targets have been employed, the measurements have been carried out

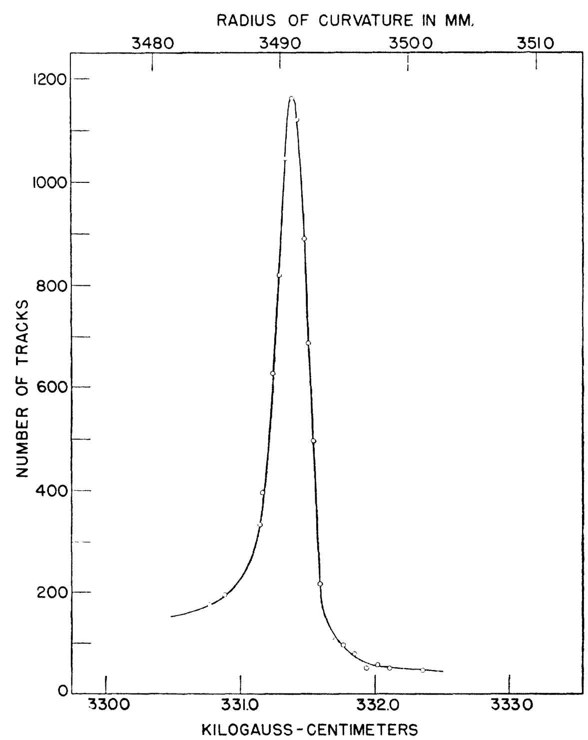


FIG. 1. Alpha-particle group from polonium used for calibration of flux meter.

[2] S. Rosenblum and G. Dupouy, Comptes rendus **194**, 1919 (1932).

from the scattering by the carbon and oxygen in the Formvar. When the measurements are made in this way, there is no uncertainty regarding the effects of surface films of carbon and oxygen. In the case of the other scattering targets, check runs must always be made to insure that these surface films, if they exist, are thin enough so that they do not appreciably affect the energy determination.

The effect of the various possible sources of error in these experiments has been carefully considered. In order to check on the possibility that a gradual accumulation of surface contaminants on the polonium source used for calibration might have occurred during the period of approximately eighteen months that it has been in the vacuum system, fresh sources were prepared at the conclusion of these experiments and were placed in the target position. The calibration constants obtained from the old and new sources agree to within 0.1 percent. The peak shown in Fig. 1 has a half-width of 0.6 mm. Measurements on this and on the other peaks obtained from thicker sources and from sources of greater width agree in indicating that the energy of the group can be taken to be that corresponding to a point on the high energy side of the peak at a height that is one-third the maximum. The measured $H\rho$ of the various groups has been found to be independent of the field strength, and this, together with the sharpness of the peaks, is a confirmation of observations made on the uniformity of the magnetic field in the region of the motion of the particles.

In making the conversion from the observed $H\rho$ values to particle energies, exact mass values have been used,[3] and relativity corrections have been made where required. In making the conversion, an uncertainty arises from the values of the fundamental physical constants that must be employed.[4] In general, errors caused by the uncertainties in the values of these constants and in the value for the $H\rho$ of polonium alpha-particles are approximately the same as the uncertainties due to the various experimental factors involved, such as the energy spread in the beam admitted through the entrance slit onto the target, the uncertainty in the angle of observation with respect to the direction of the incident particles, non-uniformities of the magnetic field at the target and at the photographic plates, the uncertainty in the effective diameter of the path in the magnet from the target to the fiducial mark placed on the photographic plate, the homogeneity of the magnetic field, the determination of the location of the peaks with respect to the fiducial marks on the plates, and the constancy and the evaluation of the magnetic field. All but the last two are systematic errors and thus appear in the same direction in the calculations of the energies of both the incident particles and the emergent ones. Thus, they tend to cancel out when energy differences are being studied, and the energy levels, as measured from the ground state, can be measured with greater accuracy than can the individual $Q$-values.

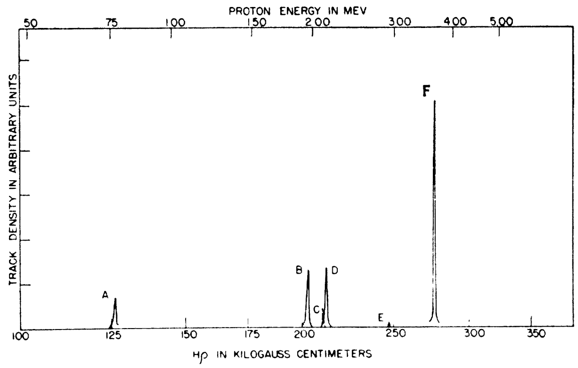


FIG. 2. Proton groups and elastically scattered deuterons from Formvar target. Peaks $A$ and $F$ are protons from $C^{12}(d,p)C^{13}$; $C$ and $E$ are from $O^{16}(d,p)O^{17}$; and $B$ and $D$ are deuterons scattered from carbon and oxygen. The incident deuteron energy was 1.386 Mev.

The largest of the experimental uncertainties arises from the measurement of the magnetic field. Thus far, it has not been feasible to increase the present sensitivity of 0.1 percent for the flux meter because of drifts in the current through the annular magnet. Since an uncertainty in the measurement of the field enters as the square in the energy determination, circuits have been constructed to stabilize the magnet current to allow an increase in the sensitivity of the flux meter. Experience has indicated that this can be increased by a factor of approximately 10. Since the uncertainty in the field measurements enters as a constant percentage in determining both the incident and emergent particle energies, those reactions with high $Q$-values have a relatively larger error expressed in Mev.

The effect of these various errors has been examined in detail for each reaction. A typical example is that of $C^{12}(d,p)C^{13}$. For this reaction, Table I shows the magnitudes of the various errors that are due to the uncertainties in the quantities listed. In this, as in all the cases herein reported, consideration has been given to the extent to which the systematic errors cancel. The internal consistency of the measurements on the various reactions is considerably better than the calculated errors indicate. In the case of the $C^{12}(d,p)C^{13}$ reaction, for example, the $Q$-value, as obtained from repeated measurements taken over the range of deuteron energies from 1.0 to 2.0 Mev, agrees to within 2 kev.

## III. EXPERIMENTAL RESULTS

In the present experiment, most of the data were taken with the energy of the incident deuterons in the neighborhood of 1.4 Mev. The proton groups observed on a series of twenty-seven plates, taken to cover the range of proton energies from 0.40 to 4.0 Mev, are

[3] K. T. Bainbridge, Preliminary Report No. 1, Nuclear Science Series, National Research Council (1948).

[4] J. W. M. Dumond and E. R. Cohen, Rev. Mod. Phys. **20**, 82 (1948).

plotted in Fig. 2. A Formvar target was used for this particular series, and the elastically scattered deuterons from this target are also shown on the figure. Except for the location of the peaks due to the scattered deuterons, similar results have been obtained with targets of platinum and of silver. For each of the groups shown, separate runs have been taken during which the energy of the incident deuterons was also carefully determined.

In the energy interval studied, which covered the region from 0- to 3.4-Mev excitation in $C^{13}$, only two groups of protons have been observed that can be attributed to the $C^{12}(d,p)C^{13}$ reaction. This is in agreement with the recent results of Heydenburg, Inglis, Whitehead, and Hafner.[5] Measurements on the energies of these groups yield the values $2.729\pm0.009$ Mev and $-0.370\pm0.003$ Mev for the reaction energies. From these data, the value $3.098\pm0.008$ Mev is obtained as the energy of the excited state in $C^{13}$. This is in good agreement with the corrected values obtained by Heydenburg, Inglis, Whitehead, and Hafner, and it confirms the corrections they applied to the range-energy relation. These values have been used to calculate the mass of $C^{13}$. Using $12.003856\pm0.000019$ for the mass of $C^{12}$, we obtain $13.007716\pm0.000022$.

One of the purposes of these experiments was to investigate the possibility of the existence of weak proton groups that might not have been observed in previous experiments of lesser resolution. A particular search was made for a group that would correspond to a level in $C^{13}$ at 0.80 Mev, the existence of which is indicated by the experiments of Merhaut and of Roy[6] on the $B^{10}(\alpha,p)C^{13}$ reaction. No evidence for such a group has been found.

Since $N^{13}$ is known to have a level of 2.34 Mev, and recent work in this Laboratory on the $C^{12}(p,\gamma)N^{13}$ reaction has shown a resonance that indicates an additional level of 3.48 Mev,[7] a search has been made for groups arising from corresponding levels in $C^{13}$. The resolution of the apparatus and the sharpness of the peaks shown in Fig. 2 indicate the absence of such additional groups. The possibility that, at the bombarding energy of 1.4 Mev, weak groups from carbon might be coincident with the oxygen groups has been eliminated by studying the observed peaks while the incident deuteron energy was varied over the range from 1 Mev to 2 Mev. It is of interest to note that the experiments of Van Patter, to which reference has been made, do not indicate a level in $N^{13}$ that would correspond to the 3.1-Mev level in $C^{13}$.

The other proton groups shown in Fig. 2 are due to the $O^{16}(d,p)O^{17}$ reaction. $Q$-values of $1.925\pm0.008$ and $1.049\pm0.007$ Mev are obtained from measurements of these groups. The energy of the excited state in $O^{17}$ is thus found to be $0.876\pm0.009$ Mev. These $Q$-values are somewhat lower than the corrected values of Heydenburg and Inglis, as reported in reference 5. The mass of $O^{17}$ has been calculated and is found to be 17.004522 $\pm0.000010$.

### IV. ACKNOWLEDGMENTS

We are indebted to Dr. John Blatt and to Professor E. P. Wigner for helpful and stimulating discussions and also to Dr. D. M. Van Patter for permission to quote his results. We are particularly grateful to Mr. Wilton Tripp, Miss Cecilia O'Brien, and Mrs. Hester Andrews for their assistance in connection with reading the photographic plates.

This work has been assisted by the Joint Program of the Office of Naval Research and the Atomic Energy Commission.

[5] Heydenburg, Inglis, Whitehead, and Hafner, Phys. Rev. **75**, 1147 (1949).

[6] R. R. Roy, Phys. Rev. **75**, 1775 (1949).

[7] D. M. Van Patter, Phys. Rev. **76**, 1264 (L) (1949).