Q Values of the $C^{12}(d,p)C^{13}$, $Be^9(d,p)Be^{10}$, and $O^{16}(d,p)O^{17}$ Reactions

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The Q values of the reactions listed above have been obtained by measuring the energies of the disintegration protons by means of an annular magnet whose magnetic field was measured and kept constant by a proton magnetic moment regulator. The energy of the incident deuterons was measured in terms of the 0.8735-Mev $F^{19}(p,\alpha'\gamma)O^{16}$ resonance. The values obtained for the above reactions are 2.732 ± 0.006 Mev, 4.591 ± 0.008 Mev, and 1.918 ± 0.008 Mev, respectively. The neutron-proton mass difference as calculated from the present data for carbon and the data given by other workers for the Q's of a closed cycle of reactions involving C^{12} and C^{13} is 0.789 ± 0.008 Mev.

INTRODUCTION

THE precise measurement of the ground-state masses and of the energy levels of light nuclei is of importance in the development of a satisfactory theory of nuclear forces. One method of approach to this problem is the measurement, by magnetic analysis, of the momenta of charged particles produced in nuclear reactions. A large annular magnet for this purpose was first designed by Cockcroft[1] and used by Rutherford[2] and his co-workers to measure accurately the energies of the natural alpha-particle groups. A magnet similar to the one of Rutherford is being used at M.I.T. by Buechner[3] and his associated in studying nuclear energy levels. A magnet based on a modification of this design has been constructed at Rice Institute. The performance of this instrument has been checked by using it to measure the Q values of several nuclear reactions previously investigated by the M.I.T. group.[4]

In the present measurements a beam of deuterons was incident on a thin target of beryllium. The target was centered in the uniform field of the magnet, and the direction of the deuterons was at about 45° to the target plane. Those protons which came off the target at an angle of about 90° with respect to the incident deuteron beam were deflected by the magnetic field and brought to a focus 180° around from the target. At this point they passed through an energy resolution slit and then were counted in a mica window proportional counter. Because the incident deuteron beam was at right angles to the field of the annular magnet and was brought to the target through the field of the magnet, the angle between the incident beam and the emitted protons was not exactly 90°. Knowledge of the magnetic field necessary to deflect the emitted protons through the slit, together with the incident deuteron energy, enables one to calculate the Q value of the reaction.

In the experiments to be described, both the method used for determining the energy of the incident deuterons and that for measuring the field of the magnet were different from those used by Buechner. In the M.I.T. work the energy of the deuterons was measured by the magnetic analysis of those elastically scattered from thin foils placed in the target position. The magnetic field was measured by means of a fluxmeter calibrated in terms of polonium alpha-particles. In the present work the energy of the incident beam was determined by means of the 0.8735-Mev $F^{19}(p,\alpha'\gamma)O^{16}$ resonance as measured by Herb[5] and his associates. The magnetic field was measured in terms of the magnetic moment of the proton.

APPARATUS AND EXPERIMENTAL METHOD

The annular magnet was constructed of S.A.E. 4815 forging steel, which has satisfactory magnetic properties and excellent machining characteristics.[6] The outside and inside diameters of the annular region of the magnet were 29.500 inches and 25.560 inches, respectively. The gap between the pole pieces was 0.562 of an inch. The magnet began to saturate at about 16,000 gauss. It was supported on a stainless steel table by 1-inch bronze ball bearings so that it could be rotated through small angles when connected to the vacuum system of the Van de Graaff generator by a sylphon. This adjustment allowed the beam to be centered accurately on the target.

The magnetic field of the annular magnet was both measured and held constant by means of a proton magnetic moment regulator designed and constructed at this laboratory by Richard D. Jones. The proton magnetic moment absorption signal was presented on an oscilloscope screen and was used to monitor visually the constancy of the magnetic field. The width of the oscilloscope sweep was found to be equal to approximately 6 gauss, and the magnetic field was held constant to within ±1.5 gauss during the runs.

The frequency of the oscillator used to provide the energy at the Larmor frequency of the protons was

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[1] J. D. Cockcroft, J. Sci. Instr. **10**, 71 (1933).

[2] Rutherford, Wynn-Williams, Lewis, and Boden, Proc. Roy. Soc. (London) **A139**, 617 (1933).

[3] Buechner, Van de Graaff, Strait, Stergiopoulos, and Sperduto, Phys. Rev. **74**, 1226 (1948).

[4] Buechner, Strait, Sperduto, and Malm, Phys. Rev. **76**, 1543 (1949), and W. W. Buechner and E. N. Strait, Phys. Rev. **76**, 1547 (1949).

[5] Herb, Snowdon, and Sala, Phys. Rev. **75**, 246 (1949).

[6] Herbert C. Roters, *Electromagnetic Devices* (John Wiley and Sons, Inc., New York, 1941), p. 48.

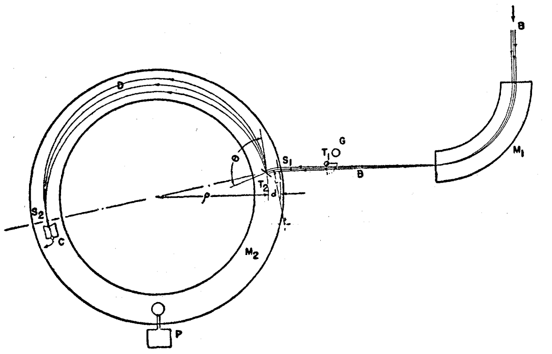

FIG. 1. Schematic diagram of the experimental arrangement: *B* is the trajectory of the bombarding deuterons; *D*, the trajectory of the disintegration particles; M_1, the 90° beam analyzing magnetic field; M_2, the annular analyzing magnet for 180° disintegration particle focusing (with radius of curvature ρ); T_1, the rotatable CaF_2 calibrating target; *G*, the Geiger counter for energy calibration with the $F^{19}(p,\alpha'\gamma)$ reaction; *d*, the distance between beam entrance slit S_1 and the target T_2; *r*, the radius of curvature of the entering deuteron mean in the magnetic field M_2; S_2, the energy resolution slit placed at the focal point; *C*, the proportion counter; and *P*, the proton moment magnetometer.

measured by means of a U.S. Army Signal Corps Frequency Meter Model No. BC-221-D. The oscillator frequency was checked often at the ends of bombardments, which lasted about 10 minutes; it was found that the drift of the oscillator during a measurement was of the order of a few thousand cycles/sec. The frequency meter was checked by beating its signal with that of radio station *WWV*.

The vacuum system placed in the annular gap of the the magnet was made by bending copper tubing of 2-inch outside diameter and $\frac{1}{16}$-inch wall thickness into the arc of a semicircle and then flattening it. The housing for the target assembly was formed of brass sides with phosphor bronze lids. This housing was silver-soldered to the copper vacuum tube and had entry ports for the beam and for the target assembly. Defining slits of chosen width could be inserted into the beam entry port. For one-half percent energy resolution, the slit width was 0.060 cm. A glass viewing port allowed the region about the target to be seen. Inside this chamber insulated silver electrodes electrically shielded the target and, when held at about 90 volts below ground, suppressed secondary electron emission from the target. The target assembly was constructed to slip very snugly into the target chamber and could be accurately repositioned. The vacuum seal was made with an "O" ring. A rod that could be rotated through a simple teflon seal carried (at 90° to each other) both the target and a quartz disk with a fine quartz fiber cemented to the disk at right angles to the rod. This arrangement allowed the beam spot on the target to be positioned precisely. A silver cylinder behind the target was carried by this assembly to stop the beam. This silver cylinder and the silver electron suppressor formed a Faraday cage for measuring the beam passing through the target.

The detector for the disintegration protons was a mica window proportional counter. This counter could be removed from a brass and phosphor bronze housing silver-soldered to the other end of the copper vacuum tube. The counter, which could be repositioned accurately, carried chosen focal plane slits in front of its window. The mica window thickness of 2.1-cm air equivalence was suffivient to stop scattered deuterons that otherwise would contribute a background of counts. The slit width for one-half percent resolution was 0.0875 cm.

The radius of curvature of the circular path from target to slit along the middle of the annular region was measured accurately by means of the calibrated screw on a milling machine. This radius was 34.895 cm. The angle which the direction of the incident deuterons made with the direction of the outgoing protons moving along the central path of the annular region, θ_0, was measured in the following manner: The deuteron beam was made to pass through a slit placed in the uniform field on the line joining the target and its focal point, and the beam was then centered on the target. The centering of the beam spot on the target was accomplished by rotating the quartz disk into the position otherwise occupied by the target. Stops on the target rotation system accurately aligned the target or quartz disk into the same position. If the distance between the slit and the target is *d* and the radius of curvature of the deuterons in the uniform field of the annular magnet is *r*, then to the first order,

$$\cos\theta_0 = -d/2r.$$

The quantity *r* was calculated from the known energy of the deuterons and the known magnetic field of the annular magnet. The distance *d* was 2.600 cm. Figure 1 schematically shows the geometry of the experimental arrangement.

The monoenergetic deuterons used in these experiments were furnished by the Rice Institute pressurized Van de Graaff accelerator[7] and 90° magnetic analyzer. The energy of the deuterons was determined in terms of the accurately measured 0.8735-Mev $(p\alpha',\gamma)$ resonance in fluorine.[5] For the energy calibration of the Van de Graaff, a target of zinc fluoride about 2 kev thick for the incident protons (as determined by weighing on a microbalance) was rotated into the beam after the 90° analysis and was bombarded with a molecular hydrogen beam. The current in the coils of the analyzing magnet of the accelerator was varied until the peak of the resonance was reached. The 90° beam analyzing magnet current was then held constant at this value while the electrostatic generator was being changed over from the acceleration of the molecular hydrogen beam to the acceleration of an atomic deuterium beam and then the (d,p) reactions were investigated. At the conclusion

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[7] Bennett, Bonner, Mandeville, and Watt, Phys. Rev. **70**, 882 (1946).

of a measurement, molecular hydrogen ions were again accelerated and the γ-ray counting rate was again determined. A 1-kev correction to the incident deuteron energy was made because of the target thickness. The difference in the masses of a deuteron and a molecular hydrogen ion were taken into account in calculating the deuteron energy. The determination of the electrostatic generator energy with the $F^{19}(p,\alpha'\gamma)O^{16}$ resonance was made with the anngular magnet off. However, when it was energized its fringing field influenced the 90° analyzer. The interaction of the field of the annular magnet with that of the analyzing magnet was measured experimentally, and this effect was corrected for in calculating the energy of the incident deuterons. The corrections to the deuteron energy were of the order of 20 kev.

The target used in the present experiments was a thin beryllium foil, about 80 $\mu g/cm^2$, kindly supplied to us by Dr. Hugh Bradner.[8] Oxygen was present on the surface of the beryllium in the form of a protective oxide, and the carbon was deposited by the action of the deuteron beam. The beryllium data were taken before any visible carbon deposit had been formed. The oxygen data were taken after a layer of carbon not over a few kev thick had been built up. The effect of the carbon deposit was taken into account in estimating the probable error to be assigned the oxygen *Q* value.

The (d,p) runs were made by measuring the proton counts per unit of charge passing through the target for various fields of the annular magnet. Since the field of the annular magnet was influenced by that of the analyzing magnet, an experiment was carried out by probing the field with the proton resonance magnetometer to give corrections to the observed frequencies due to the effect of the other magnet and to the natural inhomogeneities in the field of the annular magnet along the path of the protons from the target to the counter. The correction factors were of the order of 1.001. Some ferromagnetic materials were in the vicinity of the magnetic field: two Kovar glass seals and some iron in the proportional counter preamplifier. Probing the field in the regions of these materials, however, showed their effect was at the most one part in two thousand, and thus this small error has been neglected.

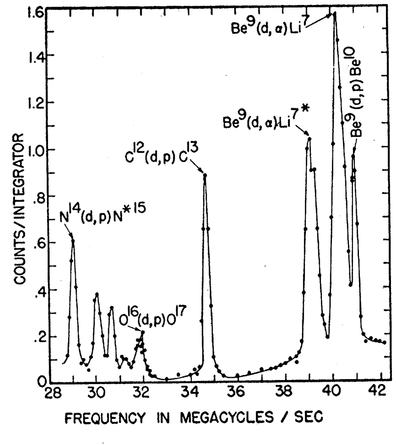

FIG. 2. The yield of disintegration particles, in arbitrary units, *versus* the magnetic field strength strength in units of Mc/sec for the bombardment of an 80 $\mu g/cm^2$ Be foil by 1747-kev deuterons.

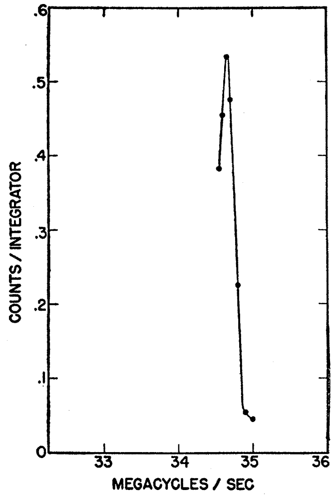

FIG. 3. Proton group from the $C^{12}(d,p)C^{13}$ reaction. The proton count per unit charge of deuterons striking the target is plotted as a function of the magnetic field as measured by the proton moment resonant frequency.

In taking data a beryllium target was first bombarded with the defining slits set to make $\Delta E/E$ one percent for the analyzed protons and the momentum position of the proton groups ascertained. These data are shown in Fig. 2. For the final experiments the energy resolution was set at one-half percent, and a fresh target was installed. Only the oxygen, beryllium, and carbon proton groups were investigated with the greater resolution. The criterion used for determining the proton energies to be associated with the observed peaks was that given by Rutherford.[2] From the observed points one-third the heights of the peaks on the high velocity side, the nonrelativistic energies of the protons were calculated by means of the following expression:

$$E_2=2(\pi^2/10^{14})(\nu_c/\nu_n)(1/\gamma)\rho^2f^2,$$

where E_2 is the proton energy in Mev; ν_c/ν_n is the ratio of the cyclotron frequency to the nuclear resonance frequency of the proton. The value used, 0.358079 ± 0.000008, is that given by Sommer *et al.*;[9] γ is the gyromagnetic ratio of the proton. The value used is that given by Thomas *et al.*:[10] $2.67528\pm0.00006\times10^4$ sec^{-1} gauss^{-1}; ρ is the average radius of curvature of the paths of the protons in the field of the annular magnet; and f is the observed "momentum" (chosen at one-third the height of the peak on the high velocity side) in cycles/sec.

The relativistic correction to the proton energy is given by $E_2^2/2m_0c^2$, where m_0c^2 is the rest energy of the proton in Mev. The mass of the proton used, 1.0081374, is that given by Tollestrup *et al.*[11] The energy equivalence of 1 atomic mass unit, 931.04 ± 0.07 Mev, is that given by Dumond and Cohen.[12]

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[8] Hugh Bradner, Rev. Sci. Instr. **19**, 662 (1948).

[9] Sommer, Thomas, and Hipple, Phys. Rev. **80**, 487 (1950).

[10] Thomas, Driscoll, and Hipple, Phys. Rev. **78**, 787 (1950).

[11] Tollestrup, Fowler, and Lauritsen, Phys. Rev. **78**, 372 (1950).

[12] J. W. M. Dumond and E. Richard Cohen, Revs. Modern Phys. **21**, 651 (1949).

TABLE I. The sources of error and estimates of their magnitude in the determination of the Q values of the (d,p) nuclear reactions for the three target nuclei indicated.

		Probable error	
Source of error	Carbon	Beryllium	Oxygen
Uncertainty in angle between directions of incident and emitted particles	2.4 kev	3.2 kev	4.0 kev
Measurement of magnetic field of annular magnet (including interaction of magnets)	2.0	2.4	1.8
Measurement of radius of curvature of particle paths	1.2	1.7	1.0
Measurement of bombarding energy (including interaction of magnets)	1.4	1.7	1.4
Determination of peak location	2.9	3.8	4.6
Target contamination	negligible	negligible	4.0
Probable error of measurement of $F^{19}(p, \alpha', \gamma)O^{16}$ resonance energy	1.5	1.4	1.5
Probable error of measurement of γ_c/γ_m and γ	0.1	0.2	0.1
Energy resolution of annular magnet	4.2	6.0	3.4

Figure 3 shows the proton yield per incident deuteron for the $C^{12}(d,p)C^{13}$ reaction plotted as a function of the magnetic field strength as measured by the proton moment resonance frequency, and is typical of the data obtained for the other groups.

The Q values of the reactions investigated were calculated from the following formula given by Livingston and Bethe:[13]

$$Q=(M_1-M_3)E_1/M_3 \\ +(M_2+M_3)E_2/M_3-2(M_1M_2E_1E_2)^{\frac{1}{2}}\cos\theta/M_3,$$

where the subscripts 1, 2, and 3 refer to the incident particle, produced particle, and residual nucleus, respectively. The M's refer to the masses and the E's to the energies of the particles in question. The values of the masses used are those given by Tollestrup *et al.*[11] θ is the angle between the directions of motion of the incident and produced particles.

The values of θ_0 for the various proton groups, calculated from the formula given previously, are as follows: carbon—92.268°; beryllium—92.862°; oxygen—92.074°. Protons whose direction of motion made a greater angle than θ_0 with the direction of the motion of the incident beam at the target could not pass through the slit in front of the counter; their energy was lower than that of those moving along the central path of the annular region, and their radius of curvature was too small to enable them to pass through the slit. Protons making a smaller angle than θ_0 with the incident beam had a higher energy than those moving along the central path and could pass through the slit. The maximum angle such protons could make with the central path and still be detected was determined by the width of the vacuum chamber at a point 90° around from the target toward the counter. This angle χ, between the tangents to the paths of the protons traveling along the central path and those just striking the wall of the vacuum chamber, was 4.25°. The average angle between the incident deuterons and emitted protons was then $\theta_0-\chi/2$. These average angles for the various proton groups measured are as follows: carbon—90.14°; beryllium—90.56°; oxygen 89.95°.

Thus to a very good approximation the average angle between incident and emitted particles in the present experiments was 90°; and since the sign of $\cos\theta$ changes about $\theta=90°$, the Q values for the reactions were calculated for an angle θ of 90°. The uncertainty in the Q obtained due to the deviation of the average angle from 90° was calculated in each case from the following expression:

$$\Delta Q=2(M_1M_2E_1E_2)^{\frac{1}{2}}\Delta\theta/M_3,$$

where $\Delta\theta$ is the deviation of the average angle between incident and emitted particles from 90°. In combining this uncertainty with the others involved in the measurement of a given Q, the whole ΔQ (instead of $\frac{1}{4}$ of it) as calculated above was included in the probable error because of the uncertainty in the measurement of the angle χ. Similarly, the value of ρ used in the calculations of E_2 was that of the average path, not the ρ as measured for the path along the middle of the annular region. This correction factor to the measured ρ was 1.0007.

RESULTS

The values obtained for the Q's of the three (d,p) reactions studied in the present work are as follows:

$C^{12}(d,p)C^{13}$ $Q=2.732\pm0.006$ Mev
$Be^9(d,p)Be^{10}$ $Q=4.591\pm0.008$ Mev
$O^{16}(d,p)O^{17}$ $Q=1.918\pm0.008$ Mev.

The probable errors given above were determined from the estimated probable errors of the various measurements. These estimates are given in Table I.

DISCUSSION

From the measured Q's of the (d,p) reactions investigated the masses of C^{13}, Be^{10}, and O^{17} can be calculated. Taking the conversion from mass to energy and the masses of C^{12} and Be^9 as given by Tollestrup *et al.*, one obtains the masses as 13.007555, 10.016756, and 17.004529, respectively, while if the more recent masses of Li *et al.*[14] are used, one obtains 13.007463, 10.016705, and 17,004529, respectively.

The neutron-proton mass difference can be calculated from the present (d,p) data for carbon and the values obtained by other workers for the Q's of a closed cycle of reactions involving C^{12} and C^{13}. Considering the

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[13] M. Stanley Livingston and H. A. Bethe, Revs. Modern Phys. **9**, 277 (1937).

[14] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951).

reactions

$$C^{12}+H^2\rightarrow C^{13}+H^1+Q_1,$$
$$C^{12}+H^2\rightarrow N^{13}+n^1+Q_2,$$
$$N^{13}\rightarrow C^{13}+2m_e+Q_3,$$

one obtains the following expression for the neutron-proton mass difference:

$$n^1-H^1=Q_1-Q_2-Q_3-2m_e.$$

The present measurements yield a value for Q_1. A value for Q_2 or -0.281 ± 0.003 Mev has been found by Bonner *et al.*,[15] and for Q_3 of 1.202 ± 0.005 Mev by Hornyak *et al.*[16] Using the value of the electron mass of 0.51079 ± 0.00006 Mev as given by Dumond and Cohen,[12] one obtains

$$n^1-H^1=0.789\pm0.008\text{ Mev}.$$

ACKNOWLEDGMENTS

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[15] Bonner, Evans, and Hill, Phys. Rev. **75**, 1398 (1949).

[16] Hornyak, Dougherty, and Lauritsen, Phys. Rev. **74**, 1727 (1948).

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Impedance Measurements on PbS Photoconductive Cells*

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It is concluded from an analysis of existing and of new impedance measurements on PbS photoconductive cells that the observed decrease in parallel resistance with frequency is attributable to a known effect of distributed capacitance and should no longer be cited as convincing evidence for the existence of internal barriers in these photocells. These results, however, should not be construed as evidence against a barrier picture.

I. INTRODUCTION

It has been postulated by Sosnowski, Starkiewicz, and Simpson[1,2] that in PbS photoconductive cells the intercrystalline contacts between *n*- and *p*-type material constitute a controlling influence on the dark resistance and photosensitivity. The most direct experimental evidence yet advanced in support of this hypothesis is Chasmar's[3] observation that the resistance component of an equivalent parallel *RC* circuit decreases with increasing frequency, ostensibly due to capacitative shunting of the intercrystalline barriers. However, according to a theory of Howe,[4] which is briefly outlined in Sec. II, even a homogeneous resistor should exhibit a decrease in parallel resistance with frequency because of distributed capacitance effects. An analysis of Chasmar's data in this light, which is presented in Sec. III, indicates that distributed capacitance represents an alternative explanation of the data. In Sec. IV new impedance measurements of our own are presented which confirm this conclusion and which in addition indicate that the barrier picture is inadequate to account quantitatively for the observed decrease with frequency of the parallel resistance. The conclusions of the present study are explicitly set forth in Sec. V along with a statement of opinion regarding the *p*–*n* barrier hypothesis.

II. THE HOWE THEORY

It has been argued by Howe[4] that if a steady potential difference is applied across a resistor R, there will be a linear fall in potential along it and an electrostatic field will be set up as indicated in Fig. 1 (a). Each pair of elements like a, a' will act like a condenser with a capacitance given by the quotient of the surface charge on the element to the potential difference between the elements. If the capacitance per unit length is assumed to be a constant C over the entire length $2l$ of the resistor and if the latter is "folded" in half, then it may be seen that the resistor is equivalent to a shorted transmission line of length l, dc resistance per unit length R/l, and capacitance per unit length C [see Fig. 1 (b)]. The impedance of such a line is

$$Z=Z_0\tanh\alpha l, \tag{1}$$

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[4] G. W. O. Howe, Wireless Engineer **12**, 291 (1935); **12**, 413 (1935); **17**, 471 (1940).