tritium (assuming zero rest mass for the neutrino), the neutron-hydrogen mass difference is obtained immediately. The Q value for the $T^3(p,n)He^3$ reaction, calculated from the threshold bombarding energy measured in the present experiment, is -764.3 ± 0.4 kev. This then is combined with the tritium beta decay end-point energy, 18.61 ± 0.02 kev,[2] yielding the neutron-hydrogen mass difference of 782.9 ± 0.4 kev. This value is in good agreement with the previously accepted value of Taschek *et al.*,[3] 782 ± 2 kev, and with the value given by Bonner and Butler,[4] 783.2 ± 2.0 kev.

VAN DE GRAAFF CALIBRATION POINT

The absolute measurement of the $T^3(p,n)He^3$ reaction threshold gives a primary energy standard calibration point at 1019.7 ± 0.5 kev for Van de Graaff accelerators. If this value is used, the same procedure for determining the threshold position should be used as is used in the present experiment. A target of tritium at least 5 kev thick should be used. The neutron detector should subtend at the target a solid angle corresponding to a cone of half-angle at least 15°, and preferably about 30° in order to avoid any critical alignment problems. The background neutron counting rate, if appreciable, should be subtracted from the total neutron counting rate, and the (net neutron counts)$^{\frac{2}{3}}$ plotted as a function of bombarding energy. The intersection with the abscissa or energy coordinate of a linear extrapolation of this curve should be designated as the reaction threshold. It is advisable, for precise calibration, to provide a method which will prevent buildup of contamination on the surface of the target. Care should be taken to avoid heating the target to the point of driving off the tritium.

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Absolute Determination of the $O^{16}(d,n)F^{17}$ Threshold Energy

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The threshold energy of the $O^{16}(d,n)F^{17}$ reaction has been measured in an absolute manner with a 2-meter radius electrostatic analyzer. The value, obtained from the intercept of the plot of (net neutron counts)$^{\frac{2}{3}}$ as a function of bombarding energy, is 1829.2 ± 0.6 kev. This threshold energy gives a reaction Q value of -1.6246 ± 0.0005 Mev, a F^{17} mass of $17.007\,499\,0\pm0.000\,003\,2$ amu, and a mass excess of 6.9828 ± 0.0030 Mev.

INTRODUCTION

PROTON bombarding energies for a number of neutron thresholds and gamma-ray resonances have been measured by absolute methods. These absolute and precise values are then used as calibration points for bombarding-particle energy measurements of other induced nuclear reactions. Within the knowledge of the authors, there exist no previous precise absolute energy measurements on other-than-proton-induced nuclear reactions, except for one absolute measurement of a He^3-induced reaction.[1]

The calibration of an energy-selecting instrument by means of proton-induced reactions is frequently inconvenient and relatively inaccurate when particles other than protons are used because a change of ion source gas is required. Furthermore, for magnetic analyzers, which are momentum sensitive, the magnetic fields required for deuterons or heavier particles correspond to protons of much higher energies. Therefore, for a given particle accelerator, the maximum-energy proton available corresponds to the same magnetic field as a much-lower-energy deuteron or heavier particle. Thus it is necessary either to extrapolate over a wide range (which for nonlinear instruments such as magnetic analyzers introduces relatively large uncertainties) or to utilize heavier proton beams, such as the H_2^+ beam. The latter procedure introduces other uncertainties.[2]

It is therefore highly desirable that absolute energy measurements be made on some nuclear reactions induced by particles other than protons. The present experiment is an absolute measurement of the (d,n) threshold energy for the target nucleus O^{16}. Since deuteron-induced *resonances* are not sufficiently sharp to permit precise measurements of the resonance energy, (d,n) thresholds offer the only means of precise comparison of deuteron energies.

The target nucleus O^{16} is convenient for use in calibrations because targets of high purity and stability can be easily prepared, and oxygen is very often a contaminant material on other targets. Furthermore, the O^{16} beams in heavy-particle linear accelerators, cyclotrons, and Van de Graaff accelerators can be calibrated from the $D^2(O^{16},n)$ threshold energy, whose value can be calculated from the $O^{16}(d,n)$ threshold. The kinematics of the two reactions make it highly desirable that the $O^{16}(d,n)$ threshold be measured very accurately, since

[1] K. L. Dunning, J. W. Butler, and R. O. Bondelid, Phys. Rev. **110**, 1076 (1958).

[2] R. O. Bondelid, J. W. Butler, and C. A. Kennedy, Bull. Am. Phys. Soc. **2**, 381 (1957); and unpublished data.

the absolute uncertainty in this measurement is greatly magnified when the $D^2(O^{16},n)$ threshold is calculated from it.

EXPERIMENTAL PROCEDURE

The deuterons were supplied by the NRL 5-Mv Van de Graaff Accelerator, and their energy was measured by a 2-meter radius electrostatic analyzer[3] adjusted to give 0.05% beam energy resolution. The absolute uncertainty from the analyzer in the energy measurement is ±0.03% (probable error).[4]

The target was protected from vacuum-system contaminants by an enclosing surface kept at liquid-nitrogen temperature.[1,5] The target, about 20 kev thick to incoming 1.8-Mev deuterons, was prepared by electrodeposition of metallic Ca onto a platinum disk, 0.010-in. thick, in an ethyl-alcohol solution, followed by oxidation of the Ca in an electric furnace at 2400°F in an oxygen atmosphere.

The neutron detector consists of three proportional counters, containing $B^{10}F_3$, embedded in a disk of paraffin 5.5 in. in diameter by 1.5 in. thick.[5] The face of the detector was about 1 in. from the target.

RESULTS AND DISCUSSION

The circles in Fig. 1 illustrate the neutron counts vs electrostatic-analyzer potentiometer setting. For reasons given in another communication,[6] the threshold energy is determined by the intercept when the net neutron counts (observed counts minus background) to the two-thirds power are plotted as a function of bombarding energy.[7] The resulting curve (the crosses in Fig. 1), assumed to be a straight line, was then determined by application of the method of least squares. The intercept thus obtained corresponds to a deuteron energy of 1829.2 kev. The uncertainty in the intercept, ±0.4 kev, is the root-mean-square of the residuals found from the horizontal straight line calculated for the background and the straight line calculated for the yield above threshold. This uncertainty in the intercept is taken to be a probable error and when combined with the probable error introduced by the uncertainty in the electrostatic analyzer parameters, ±0.03%, gives a total probable error of ±0.6 kev.

The present result, 1829.2±0.6 kev, is to be compared with previous values of 1836±3 kev by Bonner and Butler[8] and 1830±4 kev by Marion, Brugger, and Bonner.[9] These values have been corrected by the respective authors in the light of recent determinations[2,3,10,11] of resonance and threshold calibrating reactions, to yield new values of 1832±3 and 1832±4 kev, respectively. These values are then in satisfactory agreement with the present value of 1829.2±0.6 kev, even though both are somewhat higher. This is to be expected when the different methods of extrapolation to determine the threshold value are taken into account. The two previous experiments[8,9] utilized a linear extrapolation in the determination of the intercept, while in the present experiment, a two-thirds-power extrapolation is used. If a linear extrapolation of the neutron counts of Fig. 1 is made, the threshold value obtained is 1832 kev, in excellent agreement with the previous values.

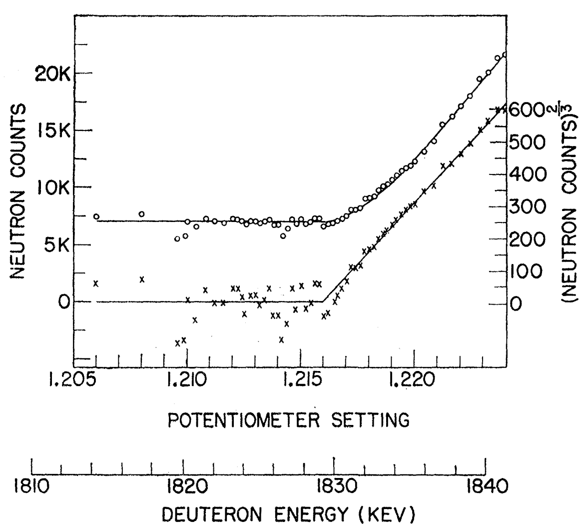

FIG. 1. Neutron yield near threshold for the $O^{16}(d,n)F^{17}$ reaction. The threshold energy is obtained from an extrapolation of the (net neutron counts)$^{\frac{2}{3}}$. The time-dependent and energy-dependent backgrounds have been subtracted from the observed neutron counts (circles).

The measured threshold energy of 1829.2±0.6 kev gives a Q value of -1.6246 ± 0.0005 Mev and a F^{17} mass of 17.007 499 0±0.000 003 2 amu, based on the mass table of Mattauch *et al.*[12] The mass excess of F^{17} is therefore 6.9828±0.0030 Mev.

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[3] R. O. Bondelid and C. A. Kennedy, Phys. Rev. **115**, 1601 (1959).

[4] Previous articles, references 1, 2, 3, and 6, reporting results obtained with the two-meter electrostatic analyzer quote a probable error of ±0.05% in the absolute energy determination. The reduction to ±0.03% in the present result is due to the use of a new gage to measure the plate separation of the analyzer. This new gage is a special application of the "Accutron Gage" manufactured by the Sheffield Corporation, Dayton, Ohio.

[5] J. W. Butler, K. L. Dunning, and R. O. Bondelid, Phys. Rev. **106**, 1224 (1957).

[6] R. O. Bondelid, J. W. Butler, A. del Callar, and C. A. Kennedy, preceding paper [Phys. Rev. **120**, 887 (1960)].

[7] Since the algebraic difference between total counts and the average background counting rate involves both plus and minus numbers, and since for plotting purposes, it is desirable that the algebraic sign be retained, the two-thirds power applies only to the absolute value of the net neutron counts, while the sign remains unchanged.

[8] T. W. Bonner and J. W. Butler, Phys. Rev. **83**, 1091 (1951).

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