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Absolute Measurement of the $T^3(p,n)He^3$ Reaction Threshold Energy and the Neutron-Hydrogen Mass Difference

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The threshold energy of the $T^3(p,n)He^3$ reaction has been precisely measured with a 2-meter radius electrostatic analyzer, calibrated by absolute methods. A clean tritiated zirconium target, protected from vacuum-system contaminants, was bombarded by protons having energy inhomogeneities as low as 0.02%. The result, obtained by an extrapolation of (net neutron counts)$^{\frac{2}{3}}$, gives a threshold value of 1019.7±0.5 kev, a reaction Q value of −764.3±0.4 kev, and a neutron-hydrogen mass difference of 782.9±0.4 kev.

INTRODUCTION

THE most precise method at present for measuring the neutron-hydrogen mass difference is the combination of the energy at the tritium beta-decay endpoint and the energy at threshold of the $T^3(p,n)He^3$ reaction.

The end-point energy for tritium has been measured by several workers,[1] the most recent measurement being that of Porter.[2] His value, presumed to be the most precise available to date, is 18.61±0.02 kev. This is in good agreement with most previous values. The $T^3(p,n)He^3$ reaction threshold has been measured by Taschek *et al.*[3] and by Bonner and Butler.[4] Their values are, respectively, 1019±1 kev and 1020.3±1.5 kev. Both of these measurements were made relative to the old absolute nuclear voltage scale established by Herb *et al.*[5] On this voltage scale a strong resonance in the Al(p,γ) reaction is given as 993.3 kev, and a strong resonance in the F$(p,\alpha\gamma)$ reaction is given as 873.5 kev. Recent work[6–8] indicates that the energy scale of Herb *et al.* is probably too high by about 1 kev in the region of 1 Mev.

The measurement of Taschek *et al.*[3] was made with a small electrostatic analyzer, having a relatively large voltage ripple on the plates, and exhibiting temperature shifts which induced changes in the calibration the order of 2 kev. The measurement of Bonner and Butler[4] was made with a magnetic analyzer which was not equipped with nuclear magnetic resonance field-measuring apparatus. The calibration energies as well as the reaction threshold energy were determined by making magnet current measurements.

Clearly, a new measurement using modern techniques is warranted.

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[2] F. T. Porter, Bull. Am. Phys. Soc. **4**, 278 (1959).

[3] R. F. Taschek, H. V. Argo, A. Hemmendinger, and G. A. Jarvis, Phys. Rev. **76**, 325 (1949).

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

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

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EXPERIMENTAL PROCEDURE

The protons were supplied by the NRL 5-Mv Van de Graaff Accelerator, and analyzed by a 2-meter radius electrostatic analyzer[6] capable of 0.01% resolution and an absolute uncertainty in the energy measurement of ±0.05%. The target was a tritiated zirconium disk backed by tungsten, obtained from the Los Alamos Scientific Laboratory by the Radiation Division of NRL. The target was "thick" for the purposes of the present experiment. The proton beam was limited to about 0.2 μa in order to preclude heating the target to the point of driving off significant amounts of tritium. The neutrons were detected by a "slow neutron detector" which consists of three BF_3 proportional counters inserted into a disk of paraffin $5\frac{1}{2}$ in. in diameter by $1\frac{1}{2}$ in. thick.[9] The axes of the counter tubes are perpendicular to the axis of the disk, which was coaxial with the proton beam. The distance between the target and the detector was varied from 2 cm to 25 cm, with 15 cm being the usual distance. The target was enclosed by a tube at liquid-nitrogen temperature in order to prevent the formation of contaminant films on the target,[6] and thus prevent displacement of the observed position of the neutron threshold.

RESULTS AND DISCUSSION

The neutron counts as a function of proton bombarding energy are shown by the circles in Fig. 1. Since the neutron counting rate curve is concave upwards, it is not a straightforward matter to extrapolate to the abscissa, and thus determine precisely the position of the reaction threshold. It has become customary to make such a linear extrapolation to determine neutron thresholds, but it is not clear that this is a proper procedure, for the following reasons.

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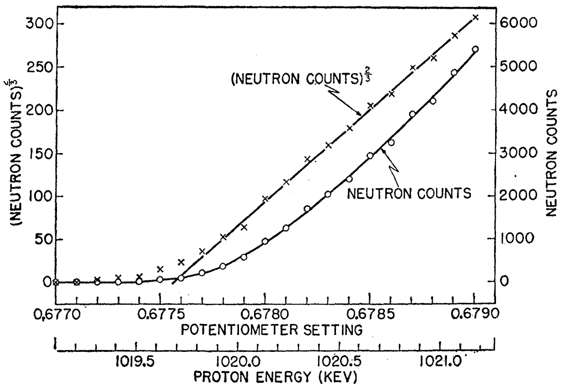

FIG. 1. Neutron yield near the threshold of the $T^3(p,n)He^3$ reaction. Note displacement of abscissa from zero.

When a neutron threshold is well removed from a resonance in the compound nucleus, the normal behavior of the neutron cross section near threshold is for neutron absorption to be proportional to $1/v$ (where v is the neutron velocity in the center-of-mass system), and neutron emission to be proportional to v. This is the well-known $1/v$ law, and is epitomized by the low-energy neutron absorption by B^{10}. Since v is proportional to (energy)$^{1/2}$, it is expected that the neutron emission near threshold would be proportional to (neutron energy)$^{1/2}$, which is in turn proportional to the (bombarding energy minus threshold energy)$^{1/2}$ or $(\Delta E)^{1/2}$. These statements hold only for s-wave neutrons. But normally, s-wave neutrons are the only ones of interest near a threshold, because the centrifugal barrier greatly attenuates the intensity of other than s-wave neutrons.

For a "thick" target, and constant cross section, the neutron yield from a reaction is expected to be proportional to ΔE. Thus, if a neutron detector subtends a solid angle at the target larger than the cone containing all of the neutrons,[4] and if the detector sensitivity is constant for the somewhat differing neutron energies in the cone, the expected counting rate, taking into account both effects discussed above, should be proportional to $(\Delta E)^{3/2}$ for a thick target. Therefore it would be expected that the counting rate vs bombarding energy curve is concave upward.

Consequently it is to be expected that plotting (net counts)$^{2/3}$ as a function of bombarding energy would produce a linear curve, and therefore an extrapolation to the abscissa would be unambiguous, thus giving a precise value for the reaction threshold energy. This curve is represented by the crosses in Fig. 1. The value of the threshold energy determined in this way is 1019.7 ± 0.5 kev. The present determination of this threshold energy has been done with an absolute calibration of the electrostatic analyzer. On the same absolute scale the $Al(p,\gamma)$ resonance (noted previously) occurs at 992.0 kev. If the previous measurements of the $T^3(p,n)$-He^3 threshold energy are normalized to this same scale, the results would be 1017.6 ± 1.0 kev for the measurement of Taschek *et al.*[3] and 1018.9 ± 1.5 kev for that of Bonner and Butler.[4] Thus, when the measurements are compared on a relative basis, with the uncertainties in the absolute scale removed, the agreement with the former value is not so good, while it is still satisfactory with the latter value.

In order to check for possible sources of error in the present measurement, the following steps were taken. Experimental runs were made for each of several different spots on the target to determine whether or not the threshold energy was dependent on the exact spot. An older Los Alamos target was used on another run. Another target, a new one made by the Oak Ridge National Laboratory, was used on still another run. The detector distances were varied from about 2 cm to 25 cm. Runs were made with two different beam analyzer resolutions, 0.05 and 0.02%. Two different target holders were used, one containing significantly more fabrication material than the other. None of the above changes in experimental situation or technique caused a shift in threshold position of more than 0.1 kev, which was the limit of repeatability.

One final check on the cleanliness of the target was made as follows. One of the targets was honed with a thoroughly cleaned carborundum stone to remove a thin surface layer and any contaminant layers, if any. The stone was previously unused and had never been oiled. Before the honing operation, the stone was boiled in nitric acid for about 30 min and in a combination of nitric and perchloric acids for about 1 hr and thoroughly washed with distilled water (about 15 washings). The honing was done under a well-ventilated hood, with rubber gloves on the operator's hands, and other normal precautions to avoid excessive contamination of the operator, and of the target holder. The hone, tweezers, and other hand tools used in the operation were discarded according to plan because of expected excessive tritium contamination. Again, there was no significant shift in the threshold value.

In order to determine whether or not the different type detector and geometry used in the Los Alamos measurements significantly affected the results, these conditions were repeated as part of the present experiment. A Los Alamos type "long counter" was placed 141 cm from the target and data taken. The solid angle cone subtended at the target by the detector was small compared with the cone containing all the neutrons at an energy several kev above the threshold. Therefore, it is not expected that the counting rate would be proportional to $(\Delta E)^{3/2}$. Actually, the counting rate curve would be expected to be somewhat concave downward. This downward concavity was observed to be the case, but if a reasonably small energy interval is chosen, a linear extrapolation gives essentially the same value for the threshold energy as determined by the other methods.

NEUTRON-HYDROGEN MASS DIFFERENCE

By combining the Q value measurement from the present experiment with that for the beta decay of

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

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