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Neutron-Hydrogen Mass Difference from the $T^3(p, n)He^3$ Reaction Threshold*

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The threshold for the $T^3(p, n)He^3$ reaction has been carefully measured using protons from the Los Alamos electrostatic generator and a thick target of tritium absorbed in a zirconium disk. The neutrons were observed at 0°, and the proton energy was measured relative to the accurately measured $Al^{27}(p, \gamma)Si^{28}$ resonance at 993.3 kev. The threshold for neutrons is found to be at a proton energy of 1019±1 kev, giving for this reaction $Q=-764\pm1$ kev. Assuming the rest mass of the neutrino to be zero, and the maximum energy of the β-particle from the decay of tritium to be 18.5 kev, 782±2 kev is obtained for the neutron-hydrogen mass difference.

INTRODUCTION

CONSIDERABLE interest in the neutron-hydrogen mass difference has been aroused by the remeasurement of the deuteron binding energy by Bell and Elliott.[1] They obtained a binding energy of 2.237±0.005 Mev measured relative to the ThC″ 2.620-Mev gamma-ray as a standard. This is approximately 50 kev higher than the previously accepted[2] deuteron binding energy. From the $H^1H^1-D^2$ separation of 1.433±0.002 Mev[3] they calculate the $n-H^1$ mass difference to be 804±9 kev. Tollestrup[4] and his collaborators have measured the Q values of the two $D-D$ reactions obtaining

$$D^2+D^2=T^3+H^1+4.036\pm0.022\text{ Mev}$$
$$=He^3+n^1+3.265\pm0.018\text{ Mev}$$

from which they calculate $n-H^1=789\pm6$ kev; the differences of the Q's is measurable with greater precision than the absolute value of either. The best previous value[2, 5] of the mass difference has been taken to be 754±5 kev.

In view of the marked discrepancy between the recent measurements and the earlier work, the present measurement is considered particularly informative. The threshold for the $T^3(p, n)He^3$ reaction gives immediately the Q of the reaction. With the additional information of the maximum energy carried away by the β-particles in the decay of tritium one can calculate the $n-H^1$ mass difference.

$$T^3+H^1=He^3+n+Q$$
$$T^3=He^3+E_\beta+\mu, \quad (1)$$

where T^3, H^1, and He^3 are atomic masses, and E_β is the maximum energy of the particle from the decay of tritium. Assuming the rest mass μ of the neutrino to be zero, one gets

$$n-H^1=(T^3-He^3)-Q$$
$$=E_\beta-Q. \quad (2)$$

E_β is known to within one kilovolt,[6] and $n-H^1$ will be known to within the sum of the errors of E_β and Q.

EXPERIMENTAL PROCEDURE

The Los Alamos electrostatic generator was used to produce a monoergic beam of protons. The energy of the generator is controlled by an electrostatic analyzer which utilizes the diatomic beam in a feedback control loop. The recently determined highly accurate nuclear energy scale of Herb, Snowdon, and Sala[7] establishes a

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[1] R. E. Bell and L. G. Elliott, Phys. Rev. **74**, 1552 (1948).

[2] W. E. Stephens, Rev. Mod. Phys. **19**, 19 (1947). D. J. Hughes, Phys. Rev. **70**, 219 (1946).

[3] R. Cohen and W. R. Hornyak, Phys. Rev. **72**, 1127 (1947).

[4] Tollestrup, Jenkins, Fowler, and Lauritsen, private communications, to be published soon.

[5] K. T. Bainbridge, *Isotopic Weights of the Fundamental Isotopes* (National Research Council, June, 1948), p. 4.

[6] E. R. Graves and D. Meyer, private communication, to be submitted for publication in Phys. Rev. J. L. McKibben and A. Shurig, private communication. G. C. Hanna and B. Pontecorvo, Phys. Rev. **75**, 983 (1949). Curran, Angus, and Cockroft, Phil. Mag. **40**, 53 (1949).

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

TABLE I. Threshold voltage for three separate runs.

Run	$Al^{27}(p, \gamma)Si^{28}$ potentiometer setting	$T^3(p, n)He^3$ potentiometer setting	$T^3(p, n)He^3$ threshold Mev
1	0.4806	0.4933	1.0197
2	0.4815	0.4942	1.0196
3	0.4815	0.4939	1.0189
			Av. = 1.019±0.001

suitable energy scale against which to calibrate the electrostatic analyzer. They have made the following three energy determinations: $Li^7(p, n)Be^7$ threshold at 1.8822±0.0002 Mev, the $Al^{27}(p, \gamma)Si^{28}$ resonance at 0.9933±0.0002 Mev, and the $F^{19}(p\alpha', \gamma)O^{16}$ resonance at 0.8735±0.0001 Mev. To make use of these three energy points, a paddle wheel type of target assembly holding four different target materials was constructed, as shown in Fig. 1. The wheel was within the vacuum system, and was rotated by a horseshoe magnet from outside, making possible a rapid switching from one target to another. For the calibration points, a freshly scraped aluminum plate about $\frac{1}{32}$ of an inch thick was placed on one of the target holders, and a crystal of LiF about one-mm thick on another. Both of these targets were "thick" for protons in the energy range to be covered.

A clean disk of zirconium was placed on the third paddle, and a "thick" target of tritium absorbed in a zirconium disk on the fourth. This type of tritium target has been developed in this laboratory by E. R. Graves, A. A. Rodriguez, M. Goldblatt, and D. Meyer.[8] Measurements on neutron yield from this target show that for protons in the neighborhood of 1.5 Mev the zirconium served to "dilute" the tritium to about one-fifteenth the concentration of an equivalent thick gaseous tritium target.

A large liquid nitrogen trap was placed near the target between the target and the oil diffusion pumps. The distance from the mouth of the pumps to the target was 3 meters. The trap was kept full of liquid nitrogen throughout the course of the experiment, and at the conclusion there was no visible darkening of the aluminum or zirconium targets, indicating that the trap was very effective in preventing oil vapor from reaching the target chamber.

The neutrons were detected at 0° with a flat energy response counter[9] placed 141 cm from the target. The gamma-rays were detected at 90° with two thin-wall G-M tubes crossed and in coincidence. A $\frac{1}{4}$-inch lead converter was used immediately in front of the first tube. The G-M tubes were placed in a lead pig having 2-in. thick walls, and the pig was hung as closely as possible to the target without being in physical contact.

Since the primary energy standard was the position of the $Al^{27}(p, \gamma)Si^{28}$ resonance at 993.3 kev, the experimental procedure was to swing the aluminum target into the path of the proton beam and run a thick target yield curve for the gamma-radiation as a function of proton energy, locating precisely the resonance on our electrostatic analyzer scale. The background was determined by running on the clean zirconium target and was found to be negligible. The LiF crystal was then swung into position in the beam and observations of the $F(p\alpha', \gamma)$ resonance and the $Li^7(p, n)Be^7$ threshold made. A calculation of the energies of these points using the calibration factor obtained by assuming the $Al(p, \gamma)$ resonance to be at 993.3 kev gave an indication of the linearity of our scale, and in addition the consistency of the three measurements precluded any gross mistakes in our observations. The Zr+T target was then swung into place and the threshold for the $T(p, n)$ reaction observed.

The proton beam was monitored with a current integrator[10] and was kept below 3 microamperes while running on the Zr+T target to prevent over-heating and driving off any of the tritium. The Al and LiF targets were run at a dull red heat with a beam of from 7 to 10 microamperes.

EXPERIMENTAL RESULTS

Figure 2 shows a set of curves obtained in a typical run. The energy scale is broken to permit sufficient expansion of the scale to show the precision of the measurements. All energy points are calibrated against the $Al(p, \gamma)$ resonance at 993.3 kev as a standard. The total widths of the $Al(p, \gamma)$ and the $F(p\alpha', \gamma)$ resonances were very close to 2 kev. Since these were thick targets, the energy at the midpoint of the rise was taken to be the resonance energy in each case. The energy ripple of the electrostatic generator has previously been estimated at one to two kev, which is closely checked by the above measured resonance widths. It will be seen from the curves that the measured energy of the $F(p\alpha', \gamma)$ resonance and the $Li(p, n)$ threshold relative to the $Al(p, \gamma)$ resonance fall within one kev of the values given by Herb, *et al.*[7] A run on a piece of metallic lithium gave an identical threshold to that found with the LiF and was done to make sure that crystal charging did not shift the energy by a few kilovolts.

The "foot" on the $T^3(p, n)He^3$ threshold curve is approximately 2-kev wide, which also is in agreement with the expected ripple of the electrostatic generator. The true threshold for the reaction is obtained by extrapolating the straight portion of the curve until it

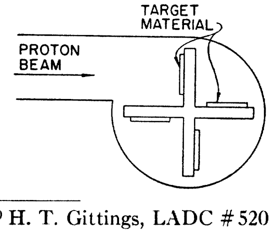

FIG. 1. Target assembly.

[8] E. R. Graves, A. A. Rodriguez, M. Goldblatt and D. Meyer, private communication, to be published in Rev. Sci. Inst.

[9] A. O. Hanson and J. L. McKibben, Phys. Rev. 72, 673 (1947).

[10] H. T. Gittings, LADC #520 (1948).

intersects the background. In this case the background is zero for all practical purposes.

The results of the three separate runs are shown in Table I. As the Al(p, γ) resonance was used as a primary calibration point for each run, the potentiometer setting corresponding to the electrostatic analyzer voltage for the resonance is listed for each run. The electrostatic analyzer controlled the energy of the incident proton beam. The potentiometer setting shifted slightly during the course of the measurements; the shift could be rather closely correlated to the time of day the measurement was being taken. Presumably this shift is a temperature effect in any or all of the energy controlling elements: the electrostatic analyzer, the resistor stack for the electrostatic analyzer and the standard cell in the potentiometer circuit. The same shift was observed in the $T^3(p, n)H^3$ threshold, but as the threshold was compared directly with the Al(p, γ) resonance measured at approximately the same time, we believe that any temperature effect has been eliminated from the final value. We wish to point out, however, that the maximum magnitude of this temperature shift was only of the order of 2 kev.

Run 3 was made after removing the zirconium +tritium disk from the target chamber and polishing it with number 600 carborundum. It was feared that an oxide coating might have built up on it prior to our use of it, but the shift in the threshold after the surface was polished was about -0.7 kev, and as this is within the voltage ripple of the machine we cannot attach much significance to it. There was essentially no neutron background below the two reaction thresholds.

The average value of the $T^3(p, n)He^3$ threshold is calculated to be 1019±1 kev. Taking $(M_T/M_T+M_H)=0.7495$ as the mass factor for transforming from the laboratory system to the center of mass system, the Q

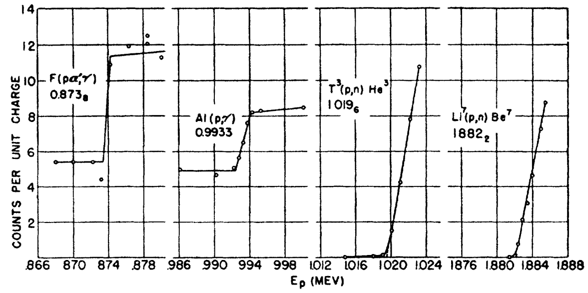

FIG. 2. Yield curves from a typical run.

value for this reaction is:

$$Q=-0.7495\times 1019=-763.7\pm 1 \text{ kev.}$$

Assuming the end point of the β-ray spectrum from the decay of tritium to be 18.5 kev[6] then from Eq. (2)

$$n-H^1=782\pm 2 \text{ kev.}$$

This is 28 kev higher than the previously accepted[2,5] value and approximately 20 kev lower than the recently determined values of Bell and Elliott.[1] The revised figures of Tollestrup, Jenkins, Fowler, and Lauritsen[4] are in agreement with these results. One calculates from this a neutron mass of 1.0089683±0.0000049 A. M. U.

Bell and Elliott had to assume the value of the $H^1H^1-D^2$ mass spectrographic doublet in obtaining their value for the $n-H^1$ difference. K. T. Bainbridge[11] has suggested that the $n-H^1$ measurement reported in this paper, together with the deuteron binding energy measured by Bell and Elliott might be a good means of checking the $H^1H^1-D^2$ doublet separation.

We wish to express our appreciation for the help given in several phases of the experiment by H. T. Gittings and G. Everhart.

[11] K. T. Bainbridge, private communication.