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The Neutron-Hydrogen Mass Difference and the Neutron Mass

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Data in the literature leading to the neutron-hydrogen mass difference and the neutron mass are summarized. The disintegration energy of the deuteron together with the HH–D mass spectroscopic doublet separation apparently yields the best value of $n-H=0.755\pm0.016$ Mev and a neutron mass of $1.008,941\pm0.000,02$ mass units. Other transmutation-radioactivity cycles check this value. Several inconsistencies in these data and their possible explanation are pointed out. Experiments of interest for improvement in accuracy and reliability of these values are noted.

INTRODUCTION

SINCE the neutron is electrically neutral and chemically inert, the usual methods of comparing atomic masses (mass spectroscope and chemical combining weights) are not applicable. The neutron mass is obviously of importance in nuclear physics. It enters into most calculations of binding energy and stability. It enters into the energy balances of all transmutations involving neutrons. The neutron-proton mass difference is of interest in the radioactivity of the neutron and in theories of a heavy particle.

Consequently, it is fortunate that nuclear reaction energies do provide an approach to the determination of the neutron mass. A combination of transmutation energies and radioactive disintegration energies or mass spectroscopic doublet separations can be used to eliminate all nuclear masses except the neutron mass minus the hydrogen atom mass. The hydrogen atom mass is used and not the proton mass since (according to custom) we shall use atomic masses throughout. This neutron-hydrogen mass difference, together, with the hydrogen atom mass, will give the neutron mass. A number of combinations of available experimental data can be used to give values for the neutron-hydrogen mass difference. Consequently, it appeared of interest to collect data leading to the neutron-hydrogen mass difference and the neutron mass and to examine their consistency, reliability, and accuracy. These values and their origin will be summarized and discussed.

DISINTEGRATION OF THE DEUTERON

The most commonly used combination of transmutation and mass spectroscopic data yielding the neutron-hydrogen mass difference involves the photo disintegration of the deuteron and the HH − D mass spectroscopic doublet.

$$_1\mathrm{D}^2 = {_0n^1} + {_1\mathrm{H}^1} + Q_\gamma,$$
$$\mathrm{HH} - \mathrm{D} = M$$

where

$$-Q_\gamma = h\nu - E_p - E_n, \quad \text{and} \quad E_p \cong E_n.$$

Adding we have

$$n - \mathrm{H} = -Q_\gamma - M.$$

A commonly used value for $n-\mathrm{H}$ has been 0.74 ± 0.06 Mev, calculated by Bethe.[1] Much more data are now available and will be considered here.

Chadwick, Feather, and Bretscher[2] used the 2.623 Mev gamma-rays from thorium C″ to disintegrate deuterium in a cloud chamber and measured the range of the disintegration protons. Using Blackett and Lees[3] range energy curve, they gave 0.185 Mev as the proton energy and $-Q=2.62-2\times0.185=2.25\pm0.05$ Mev. Using Herb's more recent values of proton ranges,[4] they estimated the proton energy as 0.2 Mev and the disintegration energy $-Q=2.22$ Mev. Bethe[1] made corrections to these data and calculated a proton energy of 0.225 Mev and $-Q=2.17\pm0.04$

[1] H. A. Bethe, Phys. Rev. **53**, 313 (1938).
[2] Chadwick, Feather, and Bretscher, Proc. Roy. Soc. **163**, 366 (1937).
[3] Blackett and Lees, Proc. Roy. Soc. **134**, 658 (1932).
[4] Parkinson, Herb, Bellamy, and Hudson, Phys. Rev. **52**, 75 (1937).

Mev. Uncertainty in the range-energy curve for protons of this low energy is the main cause for the error in this calculation.

The sodium gamma-rays have been used to give disintegration protons of somewhat larger energy. Richardson and Emo[5] observed an average proton range of 0.44 cm which they converted to 0.41 Mev. Using the Cornell 1937 range-energy curve, we can estimate an energy of 0.38 Mev for this range. Consequently, 0.76 Mev should be subtracted from the energy of the sodium gamma-ray to get $-Q_\gamma$. However, there is considerable uncertainty in the energy of the high energy gamma-ray from Na^{24}. Values of 2.76 ± 0.06[6] Mev, 2.87 ± 0.05,[7] 2.94 ± 0.06,[8] 2.97 ± 0.05,[9] 3.00 ± 0.05,[10] 3.03 ± 0.05,[11] and 3.24 ± 0.1[12] Mev have been given for this gamma-ray energy. Consequently, the Richardson and Emo results cannot yet be used to give a reliable value of Q_γ.

The gamma-rays from RaC (2.198 Mev) have also been found to disintegrate deuterium.[13] The fact that disintegration occurs with RaC gamma-rays would give an upper limit of $-Q_\gamma<2.198$ Mev except for the results of Miwa[14] and others who conclude from a study of the disintegration neutrons that RaC emits a weak gamma-ray of about 2.4 Mev. However, Kimura[15] estimated the energy of the disintegration neutrons resulting from RaC$-$D to be between 0.001 and 0.0076 Mev by finding the thickness of paraffin necessary to slow the neutrons down to the iodine capture resonance energy. He calculates $-Q_\gamma=2.189\pm0.007$ Mev. Some, as yet unpublished, work at Los Alamos[16] has been done with the MsTh gamma-ray in disintegrating deuterium and measuring the disintegration neutron energy by recoil protons in an ionization chamber. These measurements were calibrated by comparison with the recoils from Li (*pn*) neutrons of similar energy. A value of 0.195 ± 0.010 Mev was obtained for the average disintegration neutron energy which gives $-Q_\gamma=2.23\pm0.03$ Mev. Since the energy distribution of the photon neutrons is different from that of the Li (*pn*) neutrons, it is not clear whether the extrapolated values of pulse height are directly comparable.

Instead of observing the range of the disintegration protons, Rogers and Rogers[17] measured the curvature of these protons in a magnetic field. Since the protons were viewed in a cloud chamber, the protons lost energy as they traversed the cloud chamber gas and consequently increased their curvature. This spiralling and possibly small angle scattering makes the true curvature somewhat difficult to measure, but the Rogers give a value of $-Q_\gamma=2.174\pm0.05$ Mev.

Stetter and Jentschke[18] have measured the ionization produced by the disintegration protons in an ionization chamber. They calculate a value for $-Q_\gamma$ of 2.189 ± 0.022 Mev.

The threshold for the production of neutrons by bombarding deuterium with increasing energy x-rays has been observed in several laboratories. The Notre Dame value of $-Q_\gamma=2.185\pm0.006$ Mev[19] used in a recent calculation of the neutron mass[20] has a surprisingly low error ascribed to it. Since details of the absolute calibration of the voltage have not been published, it is not possible to evaluate this error. The M.I.T. value of $-Q_\gamma=2.183\pm0.012$[21] Mev is probably based on an extrapolation of the generating voltmeter calibration. The ratio of the D threshold to the Be threshold as given by Myers and Van Atta, $(2.183\pm0.012)/(1.627\pm0.010)$ compares well with the same ratio given by Wiedenbeck and Marhoefer $(2.185\pm0.006)/(1.630\pm0.006)$. This attests to the similarity between the two voltage calibrations and possibly to the accuracy of the results.

The apparently most reliable measurements

[5] Richardson and Emo, Phys. Rev. **53**, 234 (1938).
[6] Elliott, Deutsch, and Roberts, Phys. Rev. **63**, 386 (1943).
[7] Goldhaber, Klaiber, and Scharff-Goldhaber, Phys. Rev. **65**, 61 (1944); H. D. Arnett and G. Scharff-Goldhaber (unpublished) repeated this experiment and find agreement with reference 6.
[8] C. E. Mandeville, Phys. Rev. **63**, 387 (1943).
[9] Kikuchi, *et al.*, Proc. Phys. Math. Soc. Jap. **21**, 260 (1939).
[10] J. R. Richardson, Phys. Rev. **53**, 124 (1938).
[11] Curran, Dee, and Strothers, Proc. Roy. Soc. **174**, 546 (1940).
[12] Krueger and Ogle, Phys. Rev. **67**, 273 (1945).
[13] Banks, Chalmers, and Hopwood, Nature **135**, 99 (1935). Mitchell, Rasetti, Fink, and Pegram, Phys. Rev. **50**, 189 (1936).
[14] M. Miwa, Phys. Math. Soc. Japan, Proc. **22**, 560 (1940); R. D. O'Neal, Phys. Rev. **70**, 1 (1946).
[15] K. Kimura, Kyoto Coll. Sci. Mem. **22**, 237 (1940).
[16] Private communication from A. O. Hansen, identified as LADC 63.
[17] Rogers and Rogers, Phys. Rev. **55**, 269 (1939).
[18] Stetter and Jentschke, Zeits. f. Physik. **110**, 214 (1938).
[19] Wiedenbeck and Marhoefer, Phys. Rev. **67**, 54 (1945).
[20] D. J. Hughes, Phys. Rev. **70**, 219 (1946).
[21] Myers and L. C. Van Atta, Phys. Rev. **61**, 19 (1942).

TABLE I. Disintegration energy of deuterium.

Experimenter	Reference	Particle Detected	Method	Gamma-ray used	$-Q_\gamma$ value	error
Kimura	15	neutron	slowing down thickness	RaC	2.189 Mev	0.007 Mev
Stetter and Jentschke	18	proton	ionization chamber	ThC″	2.189	0.022
Myers and Van Atta	21	neutron	threshold	x-rays	2.183	0.012
	average				2.187	0.011 Mev

of the disintegration energy of deuterium are summarized in Table I.

To complete this combination of data to yield the neutron-hydrogen mass difference, we need the value of M, the HH−D mass spectroscopic doublet separation. Bainbridge and Jordan[22] give 1.424 ± 0.04 Mev which is slightly larger than Aston's value[23] of 1.414 ± 0.04 Mev. A later and apparently more accurate value is given by Mattauch[24] as 1.433 ± 0.002 Mev (1.539 millimass units). A weighted average of these values differs only slightly from the Mattauch value and we take $M=1.432\pm0.005$ Mev. We can now calculate the neutron-hydrogen mass difference to be $n-\mathrm{H}=0.755\pm0.016$ Mev. (Using only the values with the least errors attached gives 0.756 ± 0.009 Mev.)

Transmutation-Radioactivity Cycles:

An historical review of various determinations of the neutron mass is given by Stranathan.[25] Bonner[26] early realized that the neutron-hydrogen mass difference could be gotten from a transmutation-radioactive cycle. He used the (np) reaction on nitrogen,

$${}_0n^1+{}_7\mathrm{N}^{14}={}_6\mathrm{C}^{14}+{}_1\mathrm{H}^1+Q_{np},$$

and

$${}_6\mathrm{C}^{14}={}_7\mathrm{N}^{14}+{}_-\beta+E_-+\mu,$$

to give

$$n-\mathrm{H}=Q_{np}+E_-+\mu.$$

Here ${}_-\beta$ is used to indicate the emission of a negative electron. It is not used in mass-energy balancing. E_- is the maximum kinetic energy of the emitted electron. μ is the neutrino rest mass. If we take Bonner and Brubaker's value[26] of proton range, 1.06 cm, and convert it to energy by use of the Cornell revised 1937 proton range energy curve, we find $Q_{np}(\mathrm{N}^{14})=0.70$ Mev. The width of Bonner and Brubaker's proton peak is not much greater than natural straggling which attests to the reliability of their measurement. However, the range energy curve is not claimed to be better than 5 percent and this is the major error in Q_{np}. E_- was given by Ruben and Kamen[27] as 0.145 ± 0.015 Mev. While Ruben and Kamen give 19 mg/cm² of aluminum as the range of the maximum energy C^{14} electrons, more recent results[27a] give 25 mg/cm² of aluminum. Although the range energy curve is not well established in this region, a value of 140 kev is given for this range in a recent table.[27b] By using $E_-=0.145$ Mev we obtain $n-\mathrm{H}=0.845\pm0.04$ Mev which is considerably larger than the value gotten from the disintegration of the deuteron. We have here assumed the neutrino mass to be zero. A finite value would make the discrepancy even greater. An apparent check on the Bonner and Brubaker result is furnished by measurements made at Los Alamos[28] on the N^{14} (np) reaction with variable energy neutrons. By extrapolating the curve of pulse height (of disintegration protons) *versus* neutron energy to zero pulse height, a value of $Q_{np}=0.71$ Mev was obtained. However, this method assumes the pulse height to be strictly linear with proton energy. Since the ionization density varies with proton energy, it might be expected that recombination and efficiency of collection would vary with ionization density and result in a non-linear variation of total collected ionization with proton energy or, at least, not linear down to zero energy.

Huber, Huber, and Scherrer[29] find a much

[22] Bainbridge and Jordan, Phys. Rev. **49**, 883 (1936).
[23] F. W. Aston, Proc. Roy. Soc. **163**, 391 (1937).
[24] J. Mattauch, Zeits. fur. techn. Phys. **19**, 578 (1938); Phys. Rev. **57**, 1155 (1940).
[25] J. D. Stranathan, *The "Particles" of Modern Physics*, (The Blakiston Company, Pennsylvania, 1942).
[26] Bonner and Brubaker, Phys. Rev. **49**, 778 (1936).
[27] Ruben and Kamen, Phys. Rev. **59**, 349 (1941).
[27a] M. G. Inghram, Bull. Am. Phys. Soc. **21**, 16 (1946); Allen F. Reid, personal communication.
[27b] J. M. Cork, *Radioactivity and Nuclear Physics* (J. W. Edwards Bros, Inc., Michigan, 1946) Table 7.
[28] Barschall and Battat, Phys. Rev. **70**, 245 (1946).
[29] O. Huber, P. Huber, and Scherrer, Helv. Phys. Acta. **13**, 209 (1940).

lower value of $Q_{np}(N^{14})=0.55\pm0.03$ Mev by using a nitrogen filled ionization chamber and measuring the ionization produced by the protons.

In principle, any similar reaction cycle will provide the $n-\mathrm{H}$ difference.

$$\begin{aligned} {}_0n^1+{}_zA&={}_{z-1}A+{}_1\mathrm{H}^1+Q_{np},\\ {}_{z-1}A&={}_zA+{}_-\beta+E_-+\mu,\\ n-\mathrm{H}&=Q_{np}+E_-+\mu. \end{aligned}$$

Whenever Q_{np} is positive, this reaction goes with slow neutrons, and Q_{np} can be determined by measuring only the kinetic energy of the proton.

Thus, the use of He^3 in cloud chamber or ionization chamber would allow completion of the chain:

$$\begin{aligned} {}_0n^1+{}_2\mathrm{He}^3&={}_1\mathrm{H}^3+{}_1\mathrm{H}^1+Q_{np},\\ {}_1\mathrm{H}^3&={}_2\mathrm{He}^3+{}_-\beta+E_-+\mu. \end{aligned}$$

Here the value of E_- has been observed to be 0.015 ± 0.003 Mev[30] so that Q_{np} can be estimated to be 0.74 Mev, and the proton would have an energy of about 0.55 Mev for slow neutrons. Other interesting reactions would involve Li^6, B^{10}, P^{31}, and S^{32}.

The inverse of these reactions, i.e., (p, n) reactions, can be used in a similar fashion to calculate the $n-\mathrm{H}$ difference. In general

$$\begin{aligned} {}_1\mathrm{H}^1+{}_zA&={}_{z+1}A+{}_0n^1+Q_{pn};\\ {}_{z+1}A&={}_zA+{}_+\beta+2m_e+E_++\mu;\\ Q_{pn}&=(-A/A+1)E_t' \end{aligned}$$

where E_t is the threshold proton energy, and m_e is the rest mass of the electron.

$$n-\mathrm{H}=-E_+-Q_{pn}-\mu-2m_e.$$

Instead of involving the proton range energy curve, the determination of the Q_{pn} usually involves the measurement of a threshold proton energy and depends on the voltage scale and its extrapolation. One of the first accurate threshold energy determinations was made with the Westinghouse electrostatic generator[31] using C^{13} for a target. $-Q_{pn}(\mathrm{C}^{13})$ was measured to be 2.97 ±0.03 Mev. $E_+(\mathrm{N}^{13})$ has been measured by Lyman to be 1.198 ± 0.006 Mev.[32] These values give $n-\mathrm{H}=0.751\pm0.03$ Mev. However, the value of E_t and hence of Q_{pn} was based on a voltage calibration using the $F(p\gamma)$ resonance as 0.862 Mev. Later work[33] has indicated the possibility that the $F(p\gamma)$ resonance may be somewhat higher, at 0.877 ± 0.003 Mev. Until the voltage scale has been well established, there will remain an uncertainty of several percent in these thresholds. Another cycle is based on boron. $-Q_{pn}(\mathrm{B}^{11})=2.72\pm0.03$ Mev[31] and $E_+(\mathrm{C}^{11})=0.95$ ±0.03 Mev[34] giving $n-\mathrm{H}=0.749\pm0.06$ Mev.

Another interesting cycle to observe would be

$$\begin{aligned} {}_1\mathrm{H}^1+{}_6\mathrm{C}^{14}&={}_7\mathrm{N}^{14}+{}_0n^1+Q_{pn};\\ {}_6\mathrm{C}^{14}&={}_7\mathrm{N}^{14}+{}_-\beta+E_-+\mu. \end{aligned}$$

Here E_- is 0.145 Mev,[27] and E_t can be estimated to be about 0.75 Mev. This reaction would be of interest since it reverses the already observed N^{14} (np) reaction and could be used to check the Q_{np} value since $Q_{np}=-Q_{pn}$. It seems possible that sufficient C^{14} may be available to perform the experiment. The (pn) type cycle with tritium may also be practical to observe. Its threshold can be estimated to occur at about 0.99 Mev.

Another type of cycle useful for determining the $n-\mathrm{H}$ difference is the combination of a (dp) and a (dn) transformation with a radioactive disintegration. In general

$$\begin{aligned} {}_1D^2+{}_zA&={}_{z+1}(A+1)+{}_0n^1+Q_{dn},\\ {}_1D^2+{}_zA&={}_z(A+1)+{}_1\mathrm{H}^1+Q_{dp},\\ {}_{z+1}(A+1)&={}_z(A+1)+{}_+\beta+E_++2m_e+\mu \end{aligned}$$

or

$${}_z(A+1)={}_{z+1}(A+1)+{}_-\beta+E_-+\mu,$$

and

$$n-\mathrm{H}=Q_{dp}-Q_{dn}+E_-+\mu$$

or

$$=Q_{dp}-Q_{dn}-E_+-2m_e-\mu.$$

A good example of this type of cycle occurs with deuterium as the ${}_zA$ nucleus. In this case, $Q_{dn}=3.31\pm0.03$ Mev,[35] $Q_{dp}=3.98\pm0.02$ Mev,[36] and $E_-=0.015\pm0.003$ Mev,[30] giving $n-\mathrm{H}$

[30] O'Neal and Goldhaber, Phys. Rev. **58**, 574 (1940); **60**, 359 (1941).
This E_- has also been determined by other experimenters to be:
11±2 kev; private communication from Watts and Williams, identified as LADC–100.
13±5 kev; Libby and Lee, Phys. Rev. **55**, 245 (1939).
14.5 kev; C. E. Nielson, Phys. Rev. **60**, 160 (1941).
9.5±2 kev; S. C. Brown, Phys. Rev. **59**, 954 (1941).

[31] Haxby, Shoupp, Stephens, and Wells, Phys. Rev. **58**, 1035 (1940).
[32] E. M. Lyman, Phys. Rev. **55**, 234 (1939).
[33] Hanson and Benedict, Phys. Rev. **65**, 33 (1944).
[34] Barkas, *et al.*, Phys. Rev. **57**, 562 (1940); Delsasso, White, Barkas, and Creutz, Phys. Rev. **58**, 586 (1940).

TABLE II. $n-\mathrm{H}$ difference as computed from transmutation data.*

Cycle type	Nucleus	$n-\mathrm{H}$	Error
$\mathrm{D}(\gamma n)$, HH-D		0.755 Mev	0.016 Mev
(np), β	N^{14}	0.845 Mev	0.04 Mev
(pn), β	C^{13}	0.751	0.03 plus voltage scale uncertainty
	B^{11}	0.749	0.06
(dp), (dn), β	D^2	0.685	0.04
	C^{12}	0.771	0.06
(dn), β, mass doublets	C^{12}	0.734	0.02

* Average = 0.757 Mev.

$=0.685\pm0.04$ Mev. For C^{12}, $A=12$, $Z=6$, we find $Q_{dn}=-0.28\pm0.01$ Mev,[37] $Q_{dp}=2.71\pm0.05$,[38] and $E_+=1.198\pm0.006$ Mev.[32] These values give $n-\mathrm{H}=0.771\pm0.06$ Mev. However, the value of Q_{dp} for C^{12} can be calculated possibly more accurately from mass spectroscopic data. Ewald[39] gives the mass doublet $C^{12}H-C^{13}$ as 4.410 ± 0.008 millimass units. Subtracting from this $\mathrm{HH}-\mathrm{D}=1.539\pm0.002$ mMU[24] we get $Q_{dp}(C^{12})=2.673\pm0.010$ Mev. Other interesting (dp), (dn) cycles might be completed with O^{16} and C^{13} by more accurate measurements. The data on $n-\mathrm{H}$ as calculated from transmutation cycles are summarized in Table II.

DISCUSSION

In comparing the values of $n-\mathrm{H}$ given in Table II, it will be noted that only two cycles deviate from the average considerably more than their probable errors would indicate. This deviation prompts us to look more closely at these two cycles, N^{14} (np), β and D (dn), (dp), β. In general, the radioactive disintegration energies are known more accurately and appear more reliable than transmutation energies. Bonner[40] has suggested that the proton range energy curve may not be correct or possibly that the error lies in applying a range energy curve established primarily by a proton ranges measured by an ionization chamber to proton ranges in a cloud chamber calibrated with α-particles. If it be assumed that the range energy curve gives too high an energy when applied to proton cloud chamber ranges, then we can qualitatively account for the major differences in Table II. If Q_{np} as gotten from the range energy curve were too large, then, since $n-\mathrm{H}=Q_{np}+E_-+\mu$, we will find too large a value for $n-\mathrm{H}$; such is the case for N^{14}. Q_{dn} will likewise be too large if the neutron energy is determined by recoil protons in a cloud chamber (as for D) and will be unaffected where Q_{dn} is found by threshold measurements (as for C^{12}). Since $n-\mathrm{H}=Q_{dp}-Q_{dn}+E_-+\mu$, the $n-\mathrm{H}$ difference will be small for D^2 and unaffected for C^{12}, as is observed. If Q_{dp} is determined by mass spectroscopic doublets, as is possible for C^{12}, it should be lower than the Q_{dp} determined by the range energy curve, as is the case for C^{12}.

Since $-Q_\gamma=h\nu-2E_p$ in the case of the disintegration of the deuteron, and since we might expect E_p to be too large if determined by proton ranges in a cloud chamber, we might anticipate a low value of $-Q_\gamma$. Bethe's value is slightly low, but the errors overshadow the slight difference. The Los Alamos value of $-Q_\gamma$, on the other hand, is high, but involves the uncertainty of obtaining average neutron energies from maximum recoil proton energies.

Although it is not apparent why the range energy curve used for cloud-chamber ranges should be in error, the above considerations strongly suggest that its accuracy be tested whenever possible. One valuable test would be to determine the threshold energy for the (pn) reaction on C^{14} and compare with Q_{np} for the inverse reaction with N^{14}.

If we average the values in Table II, we find a value 0.757 for the $n-\mathrm{H}$ difference. This is reassuring agreement with the deuteron disintegration value. However, because of the errors and uncertainties involved in the transmutation cycles, the deuteron disintegration value is probably the most reliable. Hence we can combine it with Mattauch's[24] hydrogen mass of $1.008,130\pm0.000,0033$ to give the neutron mass as $1.008,941\pm0.000,02$ mass units. Since the neutron-proton mass difference, $n-p=n-\mathrm{H}+m_e$, we find a value for it of 1.257 ± 0.016 Mev. In the postulated radioactivity of the neutron

$$_0n^1={}_1\mathrm{H}^1+{}_-\beta+E_-+\mu.$$

[35] T. W. Bonner, Phys. Rev. **59**, 237 (1941).
[36] Oliphant, Kempton, and Rutherford, Proc. Roy. Soc. **149**, 406 (1935).
[37] Cockroft and Lewis, Proc. Roy. Soc. **154**, 261 (1936).
[38] Cockroft and Lewis, Proc. Roy. Soc. **154**, 261 (1936); calculated by Bethe, Rev. Mod. Phys. **9**, 371 (1937).
[39] H. Ewald, Z. Naturforschg. **1**, 131 (1946).
[40] Private communication

E_- is equal to the $n-\mathrm{H}$ mass difference, i.e., 0.755 Mev. If this value of maximum electron energy is put on a Sargent diagram,[41] a half-life of the order of a few hours is predicted. The use of Konopinski's analysis[42] gives a somewhat shorter half-life of 20 to 30 minutes. The uncertainty is, of course, in the constant of the Fermi interaction. Once the neutron half-life is established, then a knowledge of the disintegration energy will allow a determination of the Fermi constant, g, since the matrix element is surely one for the neutron radioactivity. Since the rarity of neutron disintegrations will make it difficult to observe the maximum energy of the radioactive electrons, the disintegration energy E_- must be determined by the $n-\mathrm{H}$ mass difference as above.

The neutrino mass was assumed equal to zero in the above discussion. An upper limit to its value may be estimated from some of the above data. Since the deuteron disintegration does not contain the neutrino mass while the radioactivity cycles do, a comparison of the $n-\mathrm{H}$ mass difference as determined by D (γn) to that calculated from the transmutation-radioactivity cycles, will show up the neutrino mass as a difference. In view of the apparent agreement and the errors involved in the measurements, only an upper limit of about 0.05 Mev or 1/10 the mass of the electron can be assigned to the neutrino mass from these data. A more sensitive comparison would involve a (dp), (dn) cycle with a positron activity compared to one with negatron activity. Since the neutrino mass enters into $n-\mathrm{H}$ as an addition for $_-\beta$, but a subtraction for $_+\beta$, a difference would involve twice the mass of the neutrino. Such comparisons necessitate more accurate measurement of transmutation cycles. In particular, the C^{12} (dn) threshold needs a precision determination. The high voltage scale needs to be accurately and absolutely determined in order to add reliability and accuracy to the (pn) and the D (γn) thresholds. Other types of cycles can be found which do not contain the neutrino mass but which have not yet been measured. Such a cycle of apparent promise would be the following:

$$
\begin{aligned}
{}_6\mathrm{C}^{13} &= {}_6\mathrm{C}^{12} + {}_0n^1 + Q_{\gamma n},\\
\mathrm{C}^{12}\mathrm{H} - \mathrm{C}^{13} &= M
\end{aligned}
$$

so that

$$n-\mathrm{H} = -Q_{\gamma n} - M.$$

Since $M = 4.410 \pm 0.008$[39] mMU, it can be estimated that 4.86 Mev x-rays will eject neutrons from C^{13}. This threshold would be useful to observe and measure. Also

$$
\begin{aligned}
{}_1\mathrm{D}^2 + {}_6\mathrm{C}^{13} &= {}_7\mathrm{N}^{14} + {}_0n^1 + Q_{dn},\\
\mathrm{C}^{13}\mathrm{H} - \mathrm{N}^{14} &= M_1,\\
\mathrm{HH} - \mathrm{D} &= M
\end{aligned}
$$

gives

$$n-\mathrm{H} = M_1 - M - Q_{dn}.$$

M_1 needs to be accurately measured and Q_{dn} determined from the threshold.

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[41] G. Gamow, *Structure of Atomic Nuclei and Nuclear Transformations*, (Oxford University Press, New York, 1939), p. 125.

[42] E. J. Konopinski, Rev. Mod. Phys. **15**, 209 (1943).