New Determination of the Deuteron Binding Energy and the Neutron Mass

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A new value for the deuteron binding energy of $B(d) = 2.388\,176\,8(24)\times 10^{-3}$ u is reported based on an absolute wavelength determination of the 2.2-MeV n-p capture γ ray. Derived values of the n-H and n-p mass differences are also given. We also derive $M_n = 1.008\,664\,919(14)$ u. We note that the uncertainties in the neutron-mass data are now dominated by uncertainties arising from mass spectroscopy.

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The deuteron binding energy $B(d)$, in addition to being a quantity of fundamental importance in nuclear physics, plays a central role in the determination of several other fundamental physical quantities. For example, the uncertainty in $B(d)$ has been the dominant uncertainty in previous determinations of the neutron mass. The deuteron binding energy also provides a critical reference energy for the determination of high-energy γ rays measured on the atomic-mass scale.[1] In this paper we present a new direct determination of $B(d)$ which provides a severalfold improvement in accuracy. We also report an improved derived value for the neutron mass.

While several methods for the determination of $B(d)$ have been employed in the past,[1,2] the most accurate strategy has involved the measurement of the energy of the ~ 2.2-MeV capture γ ray from the reaction $n+p \rightarrow d+\gamma$. This energy has been previously determined with the use of crystal diffraction spectrometers[3] and solid-state detectors.[4-7] All previous determinations have relied on an instrumental calibration obtained with a reference γ-ray line, most commonly the 411-keV transition in the ^{198}Hg β-decay daughter of the ^{198}Au nucleus. The work described here provides a determination of the wavelength of the 2.2-MeV γ ray, traceable, in a direct fashion, to the definition of the meter. The 411-keV transition was also measured in a parallel effort with the same apparatus, thereby establishing a robust connection with previous measurements of the 2.2-MeV line.

The complete procedure used in the current work involves three steps. In the first step the lattice spacing of a particular perfect single crystal of silicon was measured by simultaneous x-ray and optical interferometry.[8,9] This procedure provides an absolute measurement of the repeat distance of the particular crystal. The second step involved a comparison between the lattice spacing of the measured silicon crystal and each of two germanium perfect single crystals suitable for γ-ray diffraction. In the third step these calibrated germanium crystals were employed in a double–flat-crystal diffraction spectrometer having an absolute angle calibration. The combination of absolute crystal lattice-spacing determination and absolute angle measurement allowed, via the Bragg-Laue relation, a measurement of γ-ray wavelengths. This double-crystal diffraction instrument, known as GAMS-4, was installed at the high-flux reactor of the Institut Max von Laue–Paul Langevin. An in-pile hydrogenous target provided the source of n-p capture γ's.

The work described here concerns only the third step in this procedure. The other steps as well as the operation of a similar γ-ray spectrometer are described elsewhere.[10]

With use of existing mass spectroscopic data for hydrogen and deuterium, our value of $B(d)$ can be used to provide an improved value for the neutron mass in unified mass units. The major source of error in this new value arises from existing mass-spectroscopic data. We note that the demonstration of sub-ppm absolute γ-ray spectroscopy above 2 MeV provides the prospect of a new method for the determination of a variety of fundamental constants including $N_A h/c$ and the fine-structure constant α.

The source of n-p capture γ rays used in this measurement was a sample of ~ 2 g of Kapton plastic having a stoichiometric composition of $N_2H_{10}O_5C_{22}$. The source and its graphite holder were placed near the core of the high-flux reactor of the Institut Max von Laue–Paul Langevin.[11] The thermal neutron flux distribution is approximately Maxwellian with a peak at 1.2 Å (56 MeV) and the capture flux at the source position is $\sim 5\times 10^{14}$ cm^{-2}s^{-1}. This implied a 2.2-MeV activity of ~ 150 Ci.

The GAMS-4 spectrometer is a two-axis flat-crystal transmission instrument. Gamma rays from the in-pile source pass through a slit collimator, are diffracted by the first crystal, pass through an intercrystal collimator, are diffracted by the second crystal, pass through a third collimator, and are then detected. The measurement procedure involves rocking of the second crystal (and detector) so that its orientation is $\pm\theta_{\rm Bragg}$ from the first diffracted beam. $\theta_{\rm Bragg}$ is the Bragg angle given by $n\lambda = 2d \sin\theta_{\rm Bragg}$. The angular separation of these two diffracted beams is $2\theta_{\rm Bragg}$. Figure 1 gives a schematic picture of the two-crystal method.

The crystals were 5-cm-wide × 2.5-cm-high × ~5-mm-thick slabs of Ge oriented with the (400) planes available for diffraction. The measured a_0 spacing of these crystals has been previously reported[10] to be 0.565 782 16(8) nm at 22.5 °C (see Appendix for a discussion of absolute lattice-spacing determinations). The diffraction of short-wavelength gamma rays puts stringent requirements on crystal perfection. We note that no deviation from dynamical crystal perfection[12] was observed up to 2.2 MeV.[13]

The diffraction angles are quite small at the wavelengths reported here (~0.12° at 2.2 MeV). As a result, rather sensitive angle measurement is required. The diffraction angles are measured by polarization-sensitive Michelson interferometers which have a sensitivity and accuracy of $\sim 10^{-4}$ arc sec ($\leq 10^{-9}$ rad). The angle interferometers were calibrated by the summing to closure of the exterior angles of an optical polygon. Details of the calibration procedure (as employed in a similar instrument) are given in Ref. 10.

All data were recorded by use of the first-order (400) reflection from the Ge crystals. Approximately thirty data points were recorded in each line profile with a counting time of ~4 min/point. The peak and background counting rates were approximately 15 and 13 counts/min, respectively. The positive (+) and negative (−) $\theta_{\rm Bragg}$ profiles showed no discernible differences in width, intensity, or shape. Figure 2 shows a typical profile.

In order to determine $\theta_{\rm Bragg}$, both + and − profiles must be recorded. Because the elapsed time between these two recordings was about 2 h, the profiles were recorded in a sequence which corrected for temporal drifts. Most of the data were recorded in the sequences +, −, −, + or −, +, +, −, which compensate for linear drifts. However, some of the data were recorded in the sequences +, −, + or −, +, −. It can be shown that such sets of three profiles provide drift-corrected values for $\theta_{\rm Bragg}$ which should be weighted by 0.5 in comparison with the previous sequences. Data taken in the sequences +, −, +, − and −, +, −, + were analyzed in a fashion which is also linear-drift invariant.[14] Such analysis leads to a weighting of 0.75. A total of 52 independent Bragg-angle measurements were recorded during 15 d of beam time. The weighted average of these 52 angle measurements is 0.112 948 60(11)° at 22.5 °C. The er-

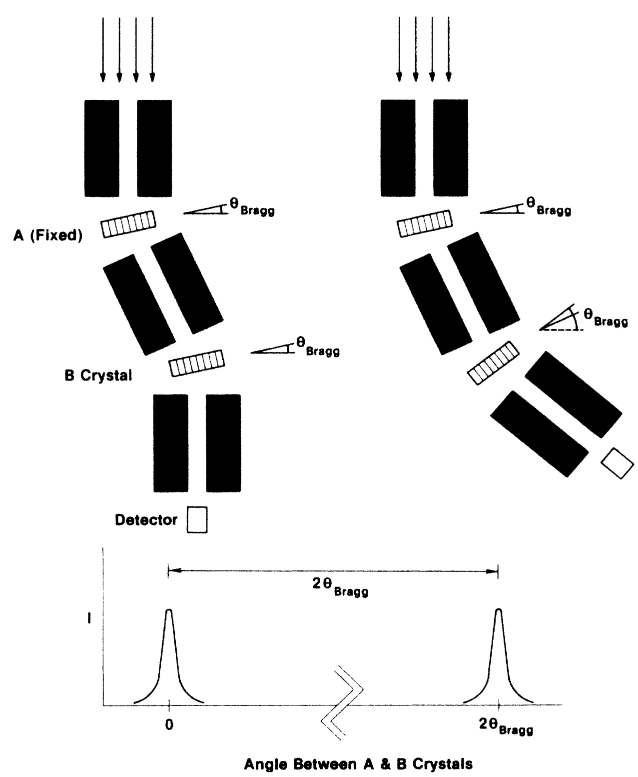

FIG. 1. Schematic of the two-crystal method. The first crystal insures that only highly collimated, nearly monochromatic radiation falls on the second, measuring crystal.

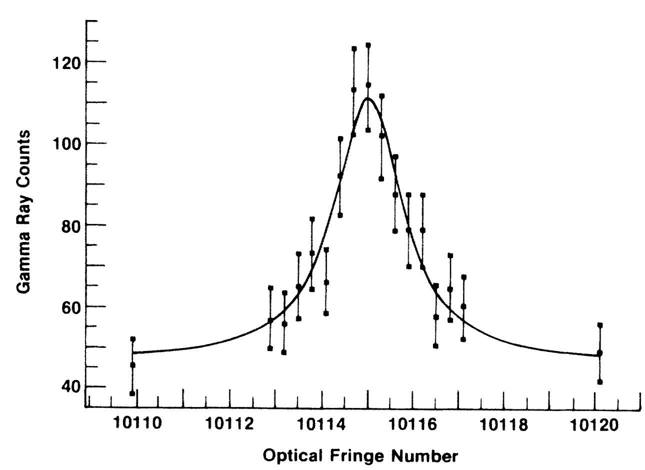

FIG. 2. Typical + scan of the n-p capture γ. The diffraction angle is ~0.12°; total range displayed is ~0.4 arc sec (2 μrad). Error bars indicate Poisson uncertainty; theoretical curve is simple Lorentzian. Data accumulation time was ~1 h. The abscissa scale refers to the difference in optical path lengths in the angle interferometer and is proportional to the sine of the crystal orientation.

ror in this angle measurement is dominated by statistical uncertainty. Contributions from systematic effects include calibration constant (0.2 ppm), temperature effects (0.3 ppm), and effects of barometric pressure (0.1 ppm).

Using the values for θ_{Bragg} and the lattice spacing for Ge we obtain a value for the wavelength λ_{np} of the n-p capture radiation of

$$\lambda_{np} = 5.576\,698\,8(55) \times 10^{-13}\ \text{m (0.98 ppm)}. \quad (1)$$

In order to obtain a value for $B(d)$ it is necessary to add the γ-ray energy to the recoil energy of the deuteron (the initial kinetic energy of the neutron $\sim \frac{1}{40}$ eV contributes a negligible broadening). It is convenient to define a quantity λ^* which corresponds to the wavelength of a (fictitious) γ ray having an energy equal to $B(d)$. It is easily shown that

$$\lambda^* = \lambda_{np}[1 + h/(2m_d c \lambda_{np})]^{-1} = 5.573\,395\,6(55) \times 10^{-13}\ \text{m}, \quad (2)$$

where m_d is the deuteron mass. All the quantities on the right-hand side of Eq. (2) are sufficiently well known that there is no reduction in accuracy when we determine λ^*.

Using the atomic-mass/wavelength conversion factor[15]

$$N_A h/c = 1.331\,025\,13(18) \times 10^{-15}\ \text{m u},$$

it is possible to obtain a value for $B(d)$ given by

$$B(d) = 2.388\,176\,3(24) \times 10^{-3}\ \text{u (1.0 ppm)}. \quad (3)$$

Previous determinations[4-7] of $B(d)$ were based on relative measurements between the 2.2-MeV n-p capture γ energy and the 411-keV γ energy from a transition in the ^{198}Hg β-decay daughter of ^{198}Au. These measurements were typically expressed in electronvolts. Note that the 411-keV γ energy was an absolute wavelength determination[10] similar to the work reported here. For the previous $B(d)$ works the conversion from wave numbers to electronvolts was accomplished by the use of a conventional value of the energy-wavelength product $E\lambda = 1.239\,852\,0 \times 10^{-6}$ eV m *exactly*. No account was taken of the large (~ 2.6 ppm) uncertainty in this product. In order to compare the current work with previous published determinations we express our value for $B(d)$ on this conventional scale. The most recent determinations of $B(d)$ are then

$$B(d) = 2\,224\,564(17)\ \text{eV}$$

(Greenwood and Chrien[4]),

$$B(d) = 2\,224\,575(9)\ \text{eV}$$

(Van der Leun and Alderliestein[5]),

$$B(d) = 2\,224\,568(8)\ \text{eV}$$

(Vylov *et al.*[6]),

$$B(d) = 2\,224\,574(9)\ \text{eV}$$

(Adam, Hnatowicz, and Kugler[7]), and

$$B(d) = 2\,224\,589\,0.0(2.2)\ \text{eV}$$

(this work).

Note that this representation of these results is only for purposes of comparison, and is not intended to suggest an accurate value of the deuteron binding energy. The historical, conventional value for the energy-wavelength product employed above is likely in error by ~ 8 ppm.[15] It is expected that the upcoming least-squares adjustment of the fundamental constants will provide a significantly improved value for this conversion constant.

As an experimental check and to provide an effective connection to earlier work, we also measured the 411-keV Au line and obtained, using the conventional $E\lambda$ value, $E_{411} = 411.804\,57(17)$ keV which can be compared with our previous reported value of $E_{411} = 411.804\,44(13)$ keV.[10] It should be noted that although these measurements employed the same germanium crystals, *all* other parts of the spectrometer were completely different. As such, the close agreement between the two 411-keV measurements gives additional confidence to the interferometric angle measurements.

The mass difference between the neutron and atomic hydrogen, $n - {}^1\text{H}$, may be determined from a knowledge of $B(d)$ and existing mass-spectroscopic data on the interval $2\,{}^1\text{H} - {}^2\text{H}$ (as calculated from raw mass-spectroscopic data presented by Wapstra and Audi[16]) by the following subtraction:

$$\begin{aligned} B(d) = {}^1\text{H} + n - {}^2\text{H} &= 2\,388\,176.3(2.4)\ \text{nu} \quad \text{(this work)}, \\ 2\,{}^1\text{H} - {}^2\text{H} &= 1\,548\,292.7(7.3)\ \text{nu} \quad \text{(Wapstra and Audi[16])} \\ \hline n - {}^1\text{H} &= 839\,883.6(7.7)\ \text{nu}. \end{aligned} \quad (4)$$

From a knowledge of $n - {}^1\text{H}$ it is possible to obtain $n - p$ by the use of the expression[17]

$$p = {}^1\text{H}[1 + (1 - \alpha^2/2) M_e/M_p]^{-1}. \quad (5)$$

Using $M_p/M_e = 1836.152\,701(37)$,[18] we find that

$$n - p = 1\,388\,449.5(7.7)\ \text{nu}.$$

The neutron mass can be obtained from knowledge of the ^{1}H mass excess of 7 825 035(12) nu.[16] Thus

$$n = 1.008\,664\,919(14)\ \text{u}\ (14\ \text{ppb}). \quad (6)$$

This result may be compared with the previously recommended value of

$$n = 1.008\,664\,904(14)\ \text{u} \quad (7)$$

from the overall atomic-mass adjustment of Wapstra and Audi. The absence of any reduction in the error between Eqs. (6) and (7) is a reflection that the error on both results is dominated by mass-spectroscopic data.

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Appendix.—The NBS measurement of the lattice spacing of Si differs by 1.8 ppm from a similar measurement at the Physikalisch-Technische Bundesanstalt (PTB) in West Germany.[19] The NBS result is $a_0 = 543\,102.997$ fm ± 0.1 ppm (at 22.5 °C, in vacuum) while the PTB result is $a_0 = 543\,102.018$ fm ± 0.06 ppm (also at 22.5 °C, in vacuum). Intercomparison of crystal samples from NBS and PTB at PTB suggests that the lattice spacings are equal to within 0.2 ppm.[20] Efforts to understand the origin of this apparent discrepancy are under way. It is expected that consistent lattice-spacing measurements accurate to $\lesssim 0.1$ ppm will be available in the near future. No allowance for this evident systematic problem has been included in the error budget given above.

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