Binding Energy of the Deuteron Measured with a Bent Crystal Spectrometer*

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The binding energy of the deuteron has been determined by measuring the energy of the neutron-proton capture gamma ray with a 2-meter bent quartz crystal spectrometer in the Cauchois geometry. A polyethylene target in the through-tube of a reactor supplied the *n-p* capture gamma rays. The 411.77-kev gamma ray of Hg^{198} and the annihilation radiation were used to calibrate the spectrometer. The average of the results of four plates gives 2.225±0.003 Mev for the binding energy of the deuteron.

ONE of the most direct methods to determine the binding energy of the deuteron consists of measuring the energy of the neutron-proton capture gamma ray. The use of a bent quartz crystal spectrometer for this purpose affords high absolute precision. We have employed a 2-meter spectrometer[1,2] in the Cauchois geometry to diffract the *n-p* capture gamma rays from a polyethylene target in the through-tube of the Livermore pool-type reactor. The present measurements are a continuation of earlier work[3] done in this laboratory.

The experimental arrangement is illustrated in Fig. 1. The polyethylene provides an effective source strength of one kilocurie. The beam is defined by a lead collimator which reduces from a width of 1.2 cm at the source to 3 mm at the crystal. This collimator remains fixed to insure that the same portion of the bent crystal is used throughout the experiment. The spectrometer is aligned with the center of the crystal and the conjugate focus on the axis of the collimator. The focussed gamma-ray line is produced at twice the Bragg angle from the beam axis. 600 μ Ilford G-5 emulsions mounted on glass are used to record the lines. The spectrometer is then rotated about the center of the crystal to reflect the gamma rays from the other side of the (310) crystal planes, forming the line pattern shown in Fig. 2. Each deuteron line required an exposure of ~140 hours.

A gold target was used to provide calibration lines. The gamma rays were the 411.770±0.036 kev gamma ray[4] from Hg^{198} and the 510.976-kev[5] annihilation radiation. The latter is presumably the result of pair production by high-energy gold-capture gamma rays in the gold target. The distances between the lines were measured with a precision comparator. For the small Bragg angles involved here, the energy of the deuteron formation gamma ray E_D may simply be calculated from

$$E_D = E_C \Delta_C / \Delta_D,$$

where E_C is the energy of the calibration gamma ray, and Δ_C, Δ_D are the separations of the lines as shown in Fig. 2. The binding energy E_B is obtained by adding 1.3 kev to E_D to account for the deuteron recoil energy.

The results from our usable plates are listed in Table I.

In the absence of instrumental errors the line pattern on each plate would be symmetrical. In other words, the pair of deuteron lines and the pair of calibration lines would have a common center. Actually, the line patterns are found to have a varying amount of asymmetry. In Table I we have listed the error in E_B which would result if the measured asymmetry were attributed completely to a shift of a deuteron line. If the asymmetry were due to a shift of a calibration line, the error in E_B would be only $\sim\frac{1}{5}$ as great. Therefore, the asymmetry error listed is probably overestimated. The fluctuation of E_B from plate to plate could be due to emulsion movements on development, judging from tests we have made. The large asymmetry on *D*-18 indicates the presence of a line shift due to an unknown cause.

A straight average of the results on all the plates gives $E_B = 2.225$ Mev. A weighted average based on the possible asymmetry errors and other smaller errors yields the same value. We therefore adopt as our overall result:

$$E_B = 2.225 \pm 0.003 \text{ Mev.}$$

The calculated probable error is less than 2 kev. How-

TABLE I. Measured values of the binding energy of the deuteron.

Plate No.	Calibration gamma ray	E_B, Mev	Possible error from asymmetry, kev
D-13	Hg^{198}	2.224	6
D-18	Hg^{198}	2.224	16
D-19	Hg^{198}, ann. rad.	2.228	3[a], 7[b]
D-20	annihilation rad.	2.222	<2

[a] For deuteron lines compared to annihilation lines.
[b] For deuteron lines compared to mercury lines.

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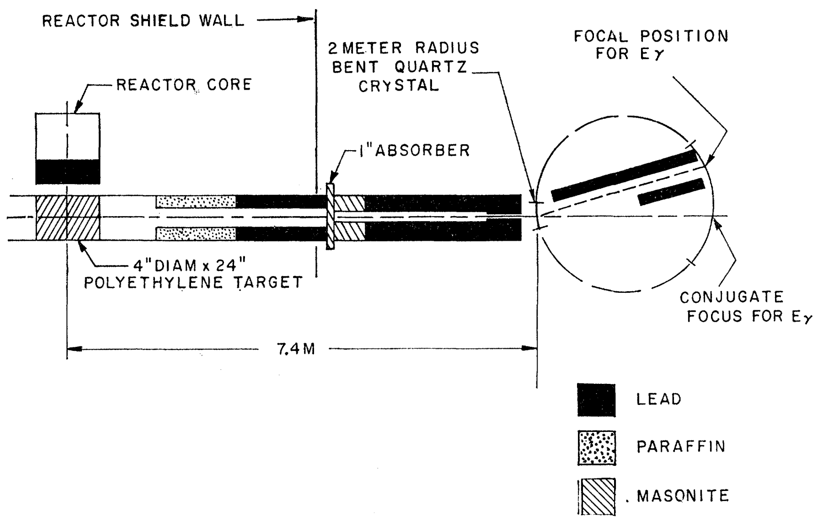

FIG. 1. Experimental arrangement.

ever, we have arbitrarily increased the estimated error to 3 kev because of the few plates and the presence of asymmetries on some of them. The 3-kev uncertainty corresponds to a determination of Δ_D to 6% of a line-width. It is to be emphasized that negligible uncertainty is introduced into the result by the calibration of the spectrometer. This is the principal advantage of the present technique.

By comparison, Bell and Elliot[6] used a beta-ray spectrometer to measure the energy of the n-p capture gamma ray, obtaining $E_B=2.230\pm0.007$ Mev. Measurements based on determining the threshold for photodisintegration of the deuteron have yielded 2.226 ±0.003 Mev,[7] and 2.227 ± 0.003 Mev.[8] Motz, Carter, and Fisher,[9] using a magnetic Compton spectrometer, have obtained a preliminary value of 2.2243 Mev.[10]

We are continuing in an effort to improve our data.

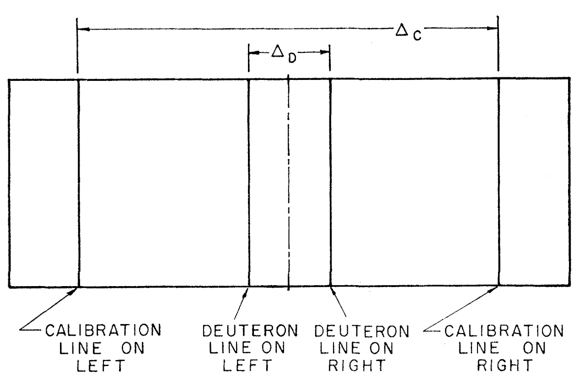

FIG. 2. Line pattern on plate (approximately full size).

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[10] *Note added in proof.* J. W. Knowles has recently measured the n-p capture gamma ray with a double flat crystal spectrometer. The preliminary result for the deuteron binding energy is 2.2270 ±0.0005 Mev according to the report CRNP 970 by B. N. Brockhouse, M. A. Clark, J. W. Knowles, J. C. D. Milton, and R. N. Sinclair, Atomic Energy of Canada Limited, Chalk River, September 22, 1960 (unpublished).