Pa^{232} has also been made[9] by the reaction $Pa^{231}(d,p)$-Pa^{232} and the half-life was found to be 33 hr. In view of the fact that this determination of the half-life was complicated by the presence of considerable amounts of the two long-lived impurities Pa^{230} (17 days) and Pa^{231}, the agreement with the measurements presented here is quite satisfactory.

The advice and assistance of W. M. Manning and G. T. Seaborg under whose general supervision this work was done are gratefully acknowledged.

[9] Osborne, Thompson, and Van Winkle, "Products of the deuteron and helium-ion bombardments of Pa^{231}," Paper No. 19.11, National Nuclear Energy Series, Division IV, Vol. 14B.

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Gamma-Rays from the Reaction $H^1(n,\gamma)D^2$ and the Binding Energy of the Deuteron

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The binding energy of the deuteron has been determined directly as 2.230±0.007 Mev by measuring the energy of the gamma-radiation from the reaction $H^1(n,\gamma)D^2$. The energy of this gamma-radiation was compared with that of the 2.615-Mev gamma-ray of ThC″ by a spectrometer study of the photo-electrons ejected from a thin uranium radiator. The probable error of 0.007 Mev includes a probable error of 0.004 Mev in the energy of the ThC″ gamma-ray.

I. INTRODUCTION

THE present paper describes a direct determination of the binding energy of the deuteron, BE(D), by measuring the energy of the gamma-radiation from the reaction $H^1(n,\gamma)D^2$ in a beta-ray spectrometer. A preliminary value of BE(D) measured in this way has been published previously.[1]

The experiments designed to measure BE(D) directly may be classified as follows: (a) photo-disintegration of the deuteron and measurement either of the energy of the emitted particles, or of the gamma-ray threshold energy for photo-disintegration; (b) synthesis of the deuteron by the reaction $H^1(n,\gamma)D^2$ and measurement of the energy of the gamma-radiation emitted at the instant of neutron capture. Many measurements have been made by method (a) and all have given values consistent with an average value of 2.187±0.011 Mev, as is given in a review by Stephens.[2] The probable error quoted for this average is low, but each of the individual experiments contains uncertainties such as an imperfect knowledge of the proton range-energy and ionization-energy relations, or an imperfect voltage calibration of high voltage generators. Method (b) is very direct but has not been used in the past for an accurate determination because of the lack of a sufficiently intense neutron source. The early attempts[3] to measure the energy of the neutron-proton recombination gamma-radiation used absorption methods and merely succeeded in showing that the energy was of the expected order of magnitude. In the present work the energy of this gamma-radiation was compared with that of the 2.615-Mev gamma-ray of ThC″ by a spectrometer study of the photo-electrons ejected from a thin uranium radiator. The result for BE(D) obtained in this experiment, 2.230±0.007 Mev, is much higher than the previously accepted value.

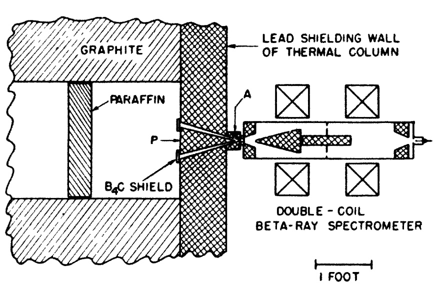

FIG. 1. Schematic diagram of the experimental arrangement used in run 1. The graphite thermal column extends to the left beyond the diagram to the reacting core of the pile.

II. EXPERIMENTAL PROCEDURE

The gamma-radiation from the reaction $H^1(n,\gamma)D^2$ was produced in paraffin irradiated with thermal neutrons. The energy of the gamma-radiation from the paraffin was measured in a beta-ray spectrometer by comparing the momenta of the photo-electrons ejected from a thin uranium radiator by this radiation and those ejected by the 2.615-Mev gamma-ray of ThC″. The ThC″ gamma-ray was chosen as a standard since its energy has been well studied and is close to that of the paraffin gamma-radiation. Two separate determinations (referred to hereafter as run 1 and run 2) were made using two slightly different experimental arrangements. In a third experiment the paraffin

[1] R. E. Bell and L. G. Elliott, Phys. Rev. **74**, 1552 (1948).
[2] W. E. Stephens, Rev. Mod. Phys. **19**, 19 (1947).
[3] R. Fleischmann, Zeits. f. Physik **103**, 113 (1936); Kikuchi, Aoki, and Husimi, Nature **137**, 186 (1936).

gamma-radiation was compared with the 2.208-Mev gamma-ray of RaC.

The experimental arrangement used in run 1 is shown schematically in Fig. 1. The spectrometer was situated outside the shielding wall of the graphite thermal column of the NRX pile. Part of the graphite was removed to admit the paraffin sample in the form of a slab of dimensions 25×25×5 in. Neutrons were prevented from escaping from the pile by the B_4C shield. The gamma-radiation from the paraffin was collimated by the lead plug *P* situated in a conical hole in the thermal column shield, into a thin conical shell of 15° half-angle converging on a uranium photo-electron radiator at the source position of the beta-ray spectrometer. The small hole *A* allowed the insertion of the ThC″ gamma-ray source behind the radiator without any mechanical motion of the experimental arrangement.

Figure 2 shows the collimating hole used in run 2 and the spectrometer arrangement common to runs 1 and 2. This collimating hole was a cone of half-angle 2.3°. The cup *C* was made of brass in run 1 and of Lucite in run 2, and had a post *B* on which the uranium radiator was mounted. The radiator was a disk of uranium metal of diameter 6 mm and superficial density 142 mg/cm^2, and could be removed for background runs. The difference between run 1 and run 2 lay mainly in the manner of collimating the gamma-rays as described above. In run 1 the paraffin gamma-radiation converged on the radiator at an angle of 15°, while in run 2 it struck it in an approximately parallel beam. In both runs the ThC″ gamma-rays struck the radiator in an approximately parallel beam.

The beta-ray spectrometer was of the magnetic lens type using two coils as shown in Fig. 1 and having baffles arranged to select negatrons with a line width at half-maximum about 2.3 percent in momentum. The detector at the focus of the spectrometer was a small end-window Geiger-Müller counter. The two lens coils were connected in series to an electronic current stabilizer supplied by a motor-generator. The current was stabilized to 1 part in 10^4 and was measured by the voltage drop across a standard resistor. A potentiometer and standard cell were used to make relative measurements of this voltage with an accuracy of 2 parts in 10^4. The shape of the secondary electron spectrum in a given momentum interval was measured by an automatic current-switching and counting device which recorded the time for a predetermined number of counts at 25 preselected successive values of the current, and repeated the process until stopped.

In each of the determinations of the energy of the paraffin gamma-radiation (i.e., in run 1 as well as in run 2) the sequence of events was as follows: A survey of 25 points separated by 1.2 percent in momentum was first made of the momentum region containing the *K* and *L* photo-electron peaks of the paraffin gamma-radiation. In order to study the peaks in detail, 25 points

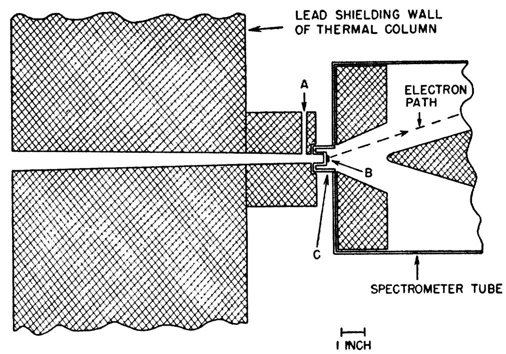

FIG. 2. Schematic diagram of the collimator arrangement of run 2 and the spectrometer arrangement common to runs 1 and 2.

spaced at intervals of 0.4 percent in momentum were measured by the automatic device about 75 times in succession, recording 1000 counts per point each time. The pile was then shut down and the ThC″ source was inserted into the hole *A*, shown in Figs. 1 and 2. The *K* and *L* photo-electron peaks of the 2.615-Mev gamma-ray were then measured both automatically and manually to a statistical accuracy comparable with that obtained for the paraffin radiation. A return was then made to the paraffin radiation and another long recording of the counts was made as before. This gave a total of about 150,000 counts at each of the 25 points of the detailed study of the paraffin radiation. During this procedure the spectrometer was not moved mechanically. Finally the U radiator was removed and background runs were made. The same general procedure was used for the comparison of the paraffin gamma-radiation with the RaC 2.208-Mev gamma-ray, using the experimental arrangement of run 2.

Between the two determinations, run 1 and run 2, the paraffin was removed from the thermal column of the pile and the secondary electron spectrum was checked to show that the gamma-radiation studied above was no longer present.

III. EXPERIMENTAL RESULTS

The experimental results of run 1 have been given previously[1] and will not be repeated in detail. The data obtained in run 2 will be given in full in order to show the method of analysis used in both runs.

Figure 3 shows the secondary electron spectrum observed in run 2 in the region of the photo-electron lines from the paraffin gamma-radiation. The main curve consists of Compton recoil electrons and *K* and *L* photo-electron peaks from the U radiator, all on a background sloping upward to the right, caused by higher energy gamma-rays from the thermal column of the pile. The shape of the background under the photo-electron peaks was measured after removing the U radiator, leaving a thick Lucite radiator. The background curve shown in Fig. 3 was obtained by normalizing these results to fit the main curve at point *A*.

A similar pair of curves for the ThC″ gamma-ray is

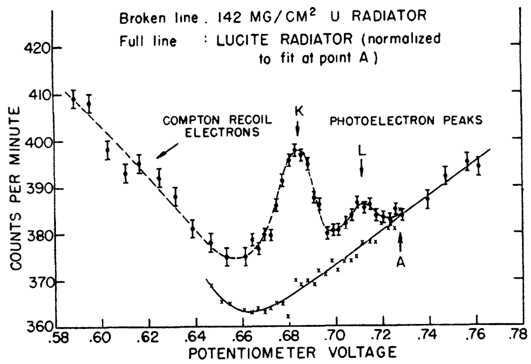

FIG. 3. Secondary electron spectrum observed in run 2 in the region of the photo-electron lines from the paraffin gamma-radiation. On the upper curve the standard deviation of each of the points is indicated by a vertical bar, and on the lower curve it is about two counts per minute.

shown in Fig. 4. The general background in this figure is much lower than that for Fig. 3 because the pile was shut off during these measurements.

In Fig. 5 both the ThC″ and paraffin photo-electron peaks are shown with their backgrounds subtracted and with the K photo-electron peaks normalized to equal heights. The potentiometer voltage scales have been adjusted in the figure to make the two K photo-electron peaks coincide on the high energy side. Any relative shift of the photo-electron peaks due to the effect of finite radiator thickness is small because the paraffin gamma-radiation is close to the standard gamma-ray in energy. We believe that any error in the relative positions of the peaks due to uncertainties in the background subtraction procedure is small because the subtraction has been done in the same manner for both curves. The horizontal bar at A in Fig. 5 indicates the magnitude of the estimated probable error in bringing the two K peaks into coincidence.

The two potentiometer voltage scales in Fig. 5 are related by the factor 1.1530, so that the ratio of the $H\rho$-values of the two photo-electron lines is 1.1530 $\pm$0.0023. Using a value of 116 kev for the K-electron binding energy of U, and Wolfson's value[4] of 2.615 $\pm$0.004 Mev for the energy of the ThC″ gamma-ray, we obtain 2.228$\pm$0.007 Mev for the energy of the paraffin gamma-radiation. Adding 1.3 kev for the recoil of the deuterium nucleus, we obtain from this run BE(D)$=$2.229$\pm$0.007 Mev.

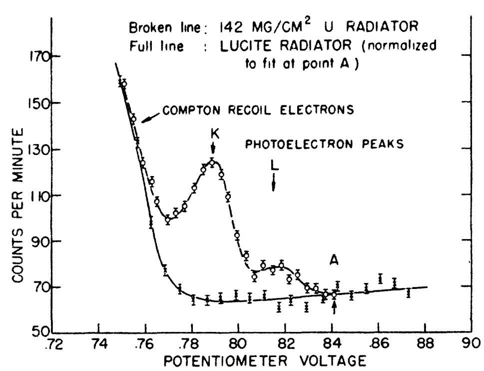

FIG. 4. Secondary electron spectrum observed in run 2 in the region of the photo-electron lines from the ThC″ gamma-ray. The standard deviations of the points on the curves are indicated by vertical bars.

The results of run 1 have been given previously[1] as BE(D)$=$2.237$\pm$0.005 Mev, relative to an assumed energy for the ThC″ gamma-ray of 2.620 Mev. Taking Wolfson's value 2.615$\pm$0.004 Mev, this becomes BE(D)$=$2.233$\pm$0.007 Mev.

The experimental results of the comparison of the paraffin gamma-radiation with the 2.208-Mev gamma-ray of RaC are shown in Fig. 6. These results cannot be used for a determination of BE(D) to an accuracy comparable with those just mentioned, mainly because the 2.208-Mev gamma-ray of RaC is weak and is badly situated in the RaC gamma-ray spectrum. The background for the RaC curve in Fig. 6 was determined at a number of points with the U radiator removed, and is indicated as a broken line. The photo-electron peaks of the 2.208-Mev gamma-ray are situated on the rise of the Compton recoil electrons from the 2.452-Mev line[4] of RaC, whose K photo-electron peak would lie at potentiometer voltage 0.744 in Fig. 6. Taking Wolfson's value of 2.208$\pm$0.006 Mev for the RaC gamma-ray, Fig. 6 yields a value BE(D)$=$2.232$\pm$0.013 Mev, in agreement with the results above. Figure 6 shows definitely that the 2.208-Mev gamma-ray of RaC is not capable of disintegrating the deuteron.

IV. DISCUSSION

In averaging the results of run 1 and run 2 to obtain the most probable value of BE(D), run 2 will be given double weight for two reasons: (1) in the experimental arrangement of run 2 the degree of collimation is closely the same for the paraffin gamma-radiation and the

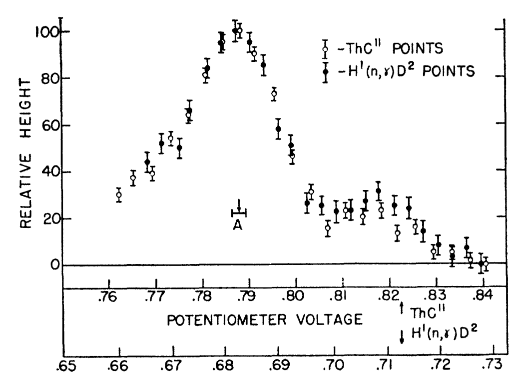

FIG. 5. The ThC″ and paraffin photo-electron peaks with backgrounds subtracted. The K photo-electron peaks have been normalized to the same height. The potentiometer voltage scales have been adjusted so as to make the two K photo-electron peaks coincide on the high energy side. The horizontal bar at A indicates the magnitude of the estimated probable error in bringing the two peaks into coincidence.

[4] J. L. Wolfson, Phys. Rev. **78**, 176 (1950).

ThC″ gamma-rays, and (2) the photo-electron peaks from the paraffin gamma-radiation stand out from the background more prominently in run 2 than in run 1. The probable errors given for runs 1 and 2 are mainly estimates of systematic errors which are not reduced by the averaging process. The average obtained in this way for the binding energy of the deuteron is

$$\mathrm{BE(D)} = 2.230 \pm 0.007 \text{ Mev.}$$

This value is determined assuming an energy of 2.615±0.004 Mev for the standard ThC″ gamma-ray. If a very much more accurate value for this latter energy should become available, a value of BE(D) with a probable error of 0.005 Mev could be computed from the above experimental data.

A value of the $(n-\mathrm{H}^1)$ energy difference can be obtained by using the above result in the equation

$$(n-\mathrm{H}^1) = \mathrm{BE(D)} - (\mathrm{H}^1\mathrm{H}^1 - \mathrm{D}^2),$$

where the $(\mathrm{H}^1\mathrm{H}^1-\mathrm{D}^2)$ difference is a mass spectrometric measurement converted to energy units. The value 1.432±0.002 Mev given for $(\mathrm{H}^1\mathrm{H}^1-\mathrm{D}^2)$ by Cohen and Hornyak[5] yields $(n-\mathrm{H}^1)=0.798\pm0.007$ Mev. Roberts and Nier[6] have recently published the value 1.442 Mev for $(\mathrm{H}^1\mathrm{H}^1-\mathrm{D}^2)$ with a probable error given as a few kilovolts. This yields the value $(n-\mathrm{H}^1)=0.788$ Mev, having a probable error exceeding 0.007 Mev by an amount depending on Roberts and Nier's error. The agreement of the latter value of $(n-\mathrm{H}^1)$ with recent determinations of this quantity by other methods[7,8] lends weight to Roberts and Nier's value for $(\mathrm{H}^1\mathrm{H}^1-\mathrm{D}^2)$.

The authors wish to express their thanks to Drs. W. B. Lewis and B. W. Sargent for interesting discussions concerning this investigation. We also wish to thank the NRX pile crew for their kind cooperation during this experiment.

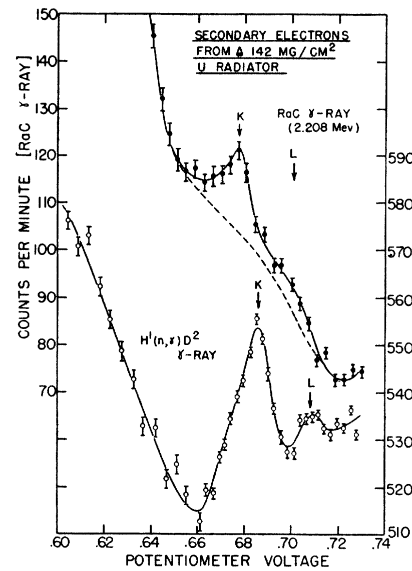

FIG. 6. Secondary electron spectra representing the comparison of the paraffin gamma-radiation with the 2.208-Mev gamma-ray of RaC. The standard deviations of the points on the curves are indicated by vertical bars.

[5] R. Cohen and W. R. Hornyak, Phy. Rev. **72**, 1127 (1947).
[6] T. R. Roberts and A. O. Nier, Phys. Rev. **77**, 746 (1950).
[7] Tollestrup, Jenkins, Fowler, and Lauritsen, Phys. Rev. **75**, 1947 (1949).
[8] Taschek, Argo, Hemmendinger, and Jarvis, Phys. Rev. **76**, 325 (1949).