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(*d,p*) Reactions in Deformed Heavy Nuclei*

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The spectra of protons from (*d,p*) nuclear reactions initiated by 11-Mev deuterons incident on Th^{232}, U^{233}, U^{235}, U^{238}, and Pu^{239} have been obtained using separated isotopic targets. The protons were analyzed in a double-focusing magnetic spectrometer. States with assignments known from radioactive-decay studies are identified and assignments for some other observed states are discussed using the Nilsson model and Satchler's theory of (*d,p*) reactions in deformed nuclei. From an analysis of the results the following binding energies of the last neutron are obtained: U^{234}, 6.83±0.11 Mev; U^{239}, 4.74±0.06 Mev; and Pu^{240}, 6.49±0.05 Mev.

I. INTRODUCTION

ALTHOUGH a large number of nuclei have deformed equilibrium shapes, no systematic study of the (*d,p*) spectra of such nuclei has been performed either in the rare-earth region or in the region of $A>220$. The high level density in nuclei in these regions makes it difficult to get accurate results with the experimental resolution presently available. The nuclei studied in this investigation are Th^{232}, U^{233}, U^{235}, U^{238}, and Pu^{239}. A number of levels are known[1] in nuclei in this region from decay scheme studies, and the first object of this investigation has been to identify some of these levels in the (*d,p*) spectra. The result of this identification is discussed in Sec. IV.A.

(*d,p*) reactions in deformed nuclei were first treated theoretically by Satchler.[2] The resolution in the present experiment is not good enough to test these calculations experimentally. However, a comparison with theory using the Nilsson model wave functions has been made in Sec. IV.B. This comparison supports some of the identifications in Sec. IV.A, and affords an explanation of the failure of the present experiment to detect the ground state of the $U^{235}(d,p)$ reaction.

A further interest in this type of investigation[3] lies in the possibility of improvement of the knowledge of neutron binding energies in the uranium region. With the present experimental technique, an accuracy of ±50 kev or better in the determination of reaction Q values is possible. However, as is discussed in Sec. IV.A, some difficulties occur in the interpretation of the data. Neutron binding energies are discussed in Sec. IV.C using the results of IV.A and IV.B.

II. EXPERIMENTAL PROCEDURE

10.7 Mev deuterons from the Indiana University cyclotron passed through a pair of quadrupole focusing magnets, a 32° sector magnet, and various beam-defining slits before entering the target chamber. Protons produced in the target were analyzed by a 180° 20-in. radius double focusing magnetic spectrometer and detected by a 20-mil CsI(Tl) scintillation crystal. All charged particles except protons were stopped just before the crystal by suitable Al absorber foils. The spectrometer image slits were set to correspond to a momentum resolution of about 0.5%. Observed particle group widths (including target thickness, beam spread, etc.) corresponded to an actual resolution in momentum of about 0.75%. Details of the experimental apparatus are described in previous references.[4,5]

No attempt was made in this study to measure the angular distributions of the emitted protons, although it is customary with this apparatus. Instead, only Q values and a few representative cross sections were determined. Proton spectra were obtained at several angles for each target in order to eliminate possible contaminant groups, as well as to give improved Q-value results. The angular distributions judged from these few points seemed to be qualitatively similar to those observed in the Pb region.[4,5]

The Q values were measured by observing proton groups from the target of interest, immediately preceded or followed by the well-known proton groups emitted by the (*d,p*) reaction in a Be target or backing used for calibration purposes. Most of the targets were prepared at Los Alamos by evaporation on to thin Be or Au backings. Target thicknesses ranged from 1–6 mg/cm², as determined by measuring the energy loss of alpha particles from a ThB deposit in the targets, using the magnetic spectrometer.

III. RESULTS

Figure 1 shows the $Th^{232}(d,p)$ spectrum which is typical for the uranium region. For $Q\lesssim 2$ Mev the gross structure is very similar in all nuclei (as has been pointed out by Northrop *et al.*[3]) with the three characteristic maxima seen in Fig. 1 around fluxmeter current 48, 51, and 53. The first gross-structure maximum occurs

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[1] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Skrifter **1**, No. 8 (1959).
[2] G. R. Satchler, Ann. Phys. **3**, 275 (1958).
[3] J. A. Northrop, R. H. Stokes, and K. Boyer, Phys. Rev. **115**, 1277 (1959).
[4] M. T. McEllistrem, H. J. Martin, D. W. Miller, and M. B. Sampson, Phys. Rev. **111**, 1636 (1958).
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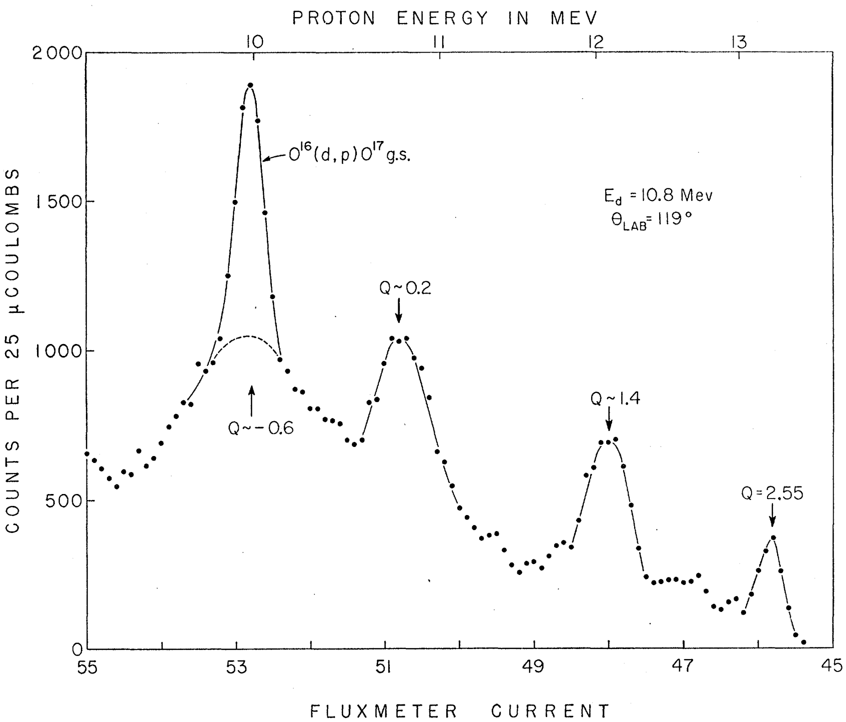

FIG. 1. A typical proton spectrum obtained for the $Th^{232}(d,p)Th^{233}$ reaction. This spectrum shows the general features exhibited by the rest of the nuclei studied in the uranium region. Similar spectra were taken at several angles for each target isotope. Proton groups from the backing material and from light-element contaminant reactions were easily identified as the angle was changed by their rapid energy shift with respect to the groups from the heavy isotopes. The strong group at 10-Mev proton energy in this figure is from the $O^{16}(d,p)O^{17}$ ground-state reaction, but it is superimposed on a broad group from Th^{232} indicated by the dashed line.

in the three uranium isotopes around $Q=1.9$ Mev, in plutonium at about $Q=2.4$ Mev, and in thorium at about $Q=1.4$ Mev. Its position thus seems to depend more on the proton than the neutron number.

On the other hand, the ground states and the low excited states show large differences from isotope to isotope. The high-energy parts of the measured (*d*,*p*) spectra of the other isotopes are shown in Figs. 2–5. It is observed that the ground-state Q values are considerably higher when the target is an odd[6] nucleus than when it is an even nucleus. U^{235} is an exception, however, but an explanation for this is offered below. Another difference between the even and odd nuclei is in the density of states close to the ground state. In the even nucleus U^{234} (Fig. 2) the distance between the two highest energy groups is 1 Mev, whereas in the odd Th^{233} (Fig. 1) they have not been resolved. However, in Pu^{240} (Fig. 5) a group has been observed at the low excitation of 0.4 Mev.

IV. DISCUSSION

A. Identification of States

During the last decade the properties of nuclei with a deformed equilibrium shape have been successfully treated[1,7,8] by the "unified nuclear model." The calculation by Nilsson of the intrinsic levels in a deformed well is of particular interest in the present work since (*d*,*p*) reactions predominantly excite single-particle states.

It was remarked above that in even nuclei the (*d*,*p*) reaction excites almost no states below an excitation of about 1 Mev except the ground states, and that these ground states have larger binding energies than the ground states in odd nuclei. These are the two well-known features of the energy gap. This is now understood[9] in terms of a nuclear model in which the two-body interaction is represented by a pairing plus a

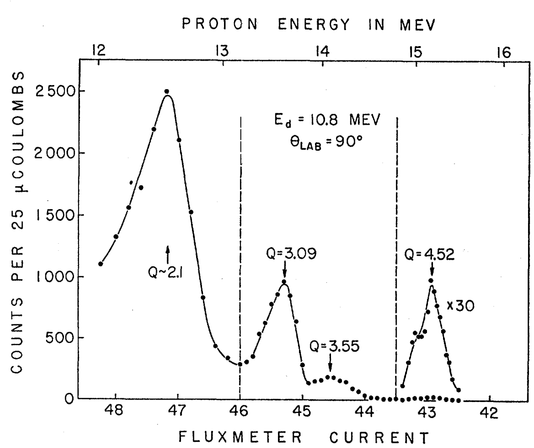

FIG. 2. Proton spectrum observed from the $U^{233}(d,p)U^{234}$ reaction using a separated isotopic target. The vertical dashed lines separate data taken in different runs.

[6] Since all the target nuclei in the investigation have an even proton number, "odd" and "even" in the following discussion refer to neutron number.

[7] A. Bohr, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **26**, No. 14 (1952). A. Bohr and B. Mottelson, *ibid.*, **27**, No. 16 (1953). A. Bohr, *Rotational States of Atomic Nuclei* (E. Munksgård, Copenhagen, 1954).

[8] S. G. Nilsson, Kgl. Danske Videnskab. Selskab. Mat.-fys. Medd. **29**, No. 16 (1955).

[9] S. T. Belyaev, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **31**, No. 11 (1959).

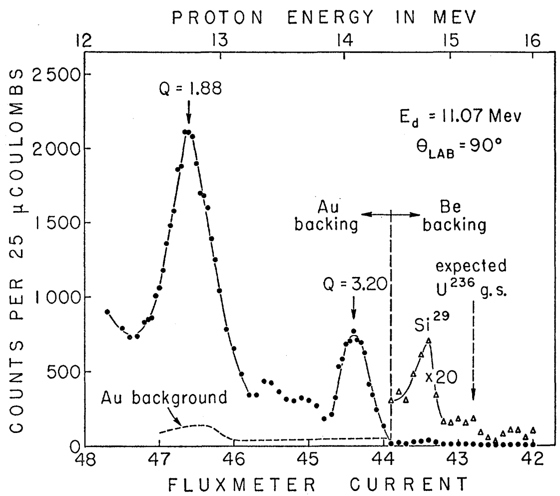

FIG. 3. Spectrum of protons obtained from the $U^{235}(d,p)U^{236}$ reaction using separated isotopic targets evaporated on backings of Au (to the left of the vertical dashed line) and Be (to the right of the vertical dashed line). The expected location for the U^{236} ground-state proton group is indicated by the dashed arrow. Counts observed to the right of the dashed line were apparently due primarily to Si^{28} contamination on the Be backing material, for separate runs with the Be backing alone looked very similar in this region. The peak location and the change in energy with spectrometer angle of the peak labeled Si^{29} were consistent with the first excited state of Si^{29}.

long-range force. Thus, although the ground-state Q values differ in even and odd nuclei, it is likely that excited states produced by adding a neutron of the same configuration to either odd or even target nuclei have about the same binding energies (i.e., Q values).

Figure 6 shows the single-particle neutron states calculated in the Nilsson model[8] as a function of the deformation. The smallest neutron number of relevance for this investigation is 141. The model assignment for this neutron is $\frac{5}{2}+[633]$ which is indeed believed to be the ground state of ${}_{92}U_{141}{}^{233}$. Thereafter follow $\frac{7}{2}-[743]$ (ground state of ${}_{92}U_{143}{}^{235}$) and $\frac{1}{2}+[631]$ (${}_{94}Pu_{145}{}^{239}$). Mottelson and Nilsson[1] discuss states up to $N=151$, i.e., $\frac{5}{2}+[622]$, $\frac{7}{2}+[624]$, and $9/2-[734]$. Data are not available for assignments beyond this neutron number, but these authors point out that $N=152$ seems to be a "half-magic" number with an energy gap of about 300 kev between the orbitals of the 151st and 153rd neutron.

Angular distributions and absolute cross sections are normally required in order to determine spin assignments for residual nuclear states excited by (d,p) reactions. However, in previous investigations in the lead region at 11-Mev deuteron energy,[4,5] it has been shown that the angular distributions differ very little for various l_n. Furthermore, since the rotational bands have not been resolved in this experiment, no definite angular momentum can be ascribed to the observed groups on this basis. However, in the lead region it was found that the magnitudes of the cross sections still depend on the angular momenta of the captured neutrons. Therefore, cross-section magnitudes will be used in the interpretation of the data, together with available information on known states. In the present section the discussion is only qualitative, but a quantitative treatment is attempted in Sec. IV.B.

Since the ground states of even nuclei lie well below any other single-particle states in binding, they are easily identified. Thus, an unambiguous idea of how strongly the 141st, 143rd, and 145th neutron states are excited[10] is obtained from the U^{233}, U^{235}, and Pu^{239} (d,p) reactions. The experimental results indicate that the cross section is small for the 141st neutron ($\frac{5}{2}+[633]$), is still smaller for the 143rd ($\frac{7}{2}-[743]$) (as the ground state was not even observed, see the discussion in Secs. IV.B and IV.C), but is considerably larger for the 145th ($\frac{1}{2}+[631]$). With the even targets the situation is much less clear. Here the single-particle level density near the ground state is comparable to the experimental resolution, and unfortunately not even the properties of the ground states in the nuclei formed in the (d,p) reaction (Th^{233} and U^{239}) are known. The ${}_{90}Th_{143}{}^{233}$ ground state is expected to be $\frac{7}{2}-[743]$ and the first excited state $\frac{1}{2}+[631]$. The $\frac{7}{2}-$ state is expected to have a small cross section, so that it appears that the highest energy proton group in the Th^{233} spectrum represents the $\frac{1}{2}+[631]$ state.[11] The ${}_{92}U_{147}{}^{239}$ ground state and first excited state are expected to be $\frac{5}{2}+[622]$ and $\frac{7}{2}+[624]$, respectively. Experimentally only one peak is observed and no direct evidence exists as to which state it represents.

It was mentioned above that corresponding states in the different isotopes could be expected to show about the same Q value. The state that seems to have the highest cross section in the region considered is $\frac{1}{2}+[631]$.

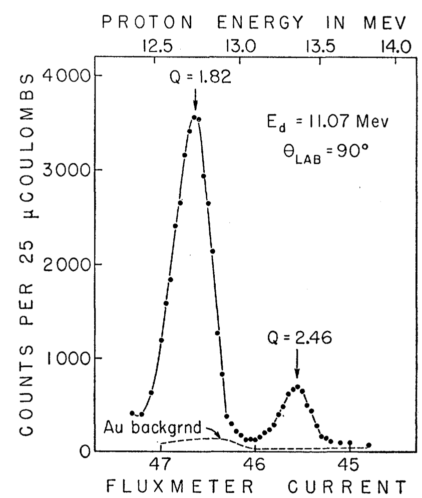

FIG. 4. High-energy portion of a spectrum of protons obtained from the $U^{238}(d,p)U^{239}$ reaction. The contribution to the results of the Au backing of the target is indicated by the dashed line.

[10] Actually the 142nd, 144th, and 146th, but their *relative* reduced widths are the same.

[11] For a further discussion, see Sec. IV.C.

This is the ground state of Pu^{239} and cannot be expected to appear in U^{239} (where this orbital is filled), but by the above interpretation it is believed to correspond to the highest energy group leading to Th^{233}. A noticeable feature in the high-energy parts of the spectra of U^{234} and U^{236} are the proton groups which have Q values of 3.09 and 3.20 Mev. It seems reasonable that these excited states represent the ground-state neutron coupled to $\frac{1}{2}+[631]$. The orbital containing the 141st neutron is filled in all the nuclei investigated except U^{233}, and the cross section for the 143rd neutron is negligible. Hence these states should be unimportant for the excited spectra. The 151st neutron state ($9/2-[734]$) wave function is very similar to the 143rd, so that its cross section is also expected to be very small. Thus the relevant neutron states remaining are $\frac{5}{2}+[622]$ and $\frac{7}{2}+[624]$. However, no groups can easily be singled out in the region of the spectrum between the suggested $\frac{1}{2}+[631]$ state and the first prominent peak at higher excitation. In the U^{236} spectrum two peaks are seen in this region, but in U^{234} and Th^{233} no structure is apparent. Finally, at an excitation of 0.5–1.4 Mev in Pu^{240} at least two groups are excited. It is thus not possible to trace the $\frac{5}{2}+[622]$ and $\frac{7}{2}+[624]$ states in the spectra.

The two groups around a fluxmeter current of 45 in Pu^{240} have an excitation of about 1 Mev and can therefore be of single-particle origin. However, it is clear from Fig. 5 that even at an excitation of 0.4 Mev a group is observed. This group cannot be a rotational state since at this excitation one would have an 8+ state, implying an $l_n=8$ transition. Neither is it likely to have a single-particle configuration other than the ground state because of the energy gap.

The expected gap at N = 152 can presumably be seen in U^{239} where a gap of more than 0.5 Mev is clearly present between the highest energy group and the first large group in the gross structure. From alpha decay systematics[12] a gap of 0.3 Mev has been observed. Since the large group is probably due mostly to the 155th neutron (see Sec. IV.B) and the cross section of the 153rd neutron is expected to be small, the agreement is reasonable. In the other nuclei the gap is more or less obscured.

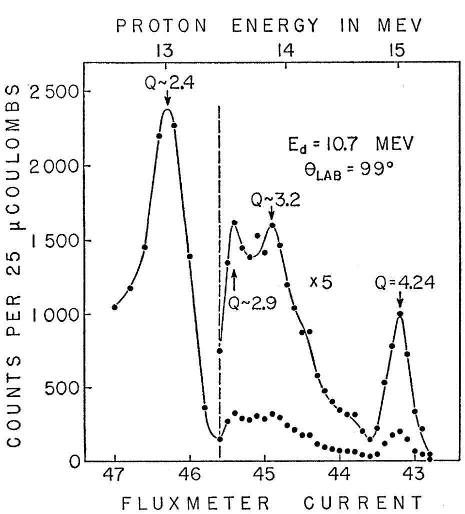

FIG. 5. Proton spectrum observed from the $Pu^{239}(d,p)Pu^{240}$ reaction, using an isotopic target evaporated on a Be backing.

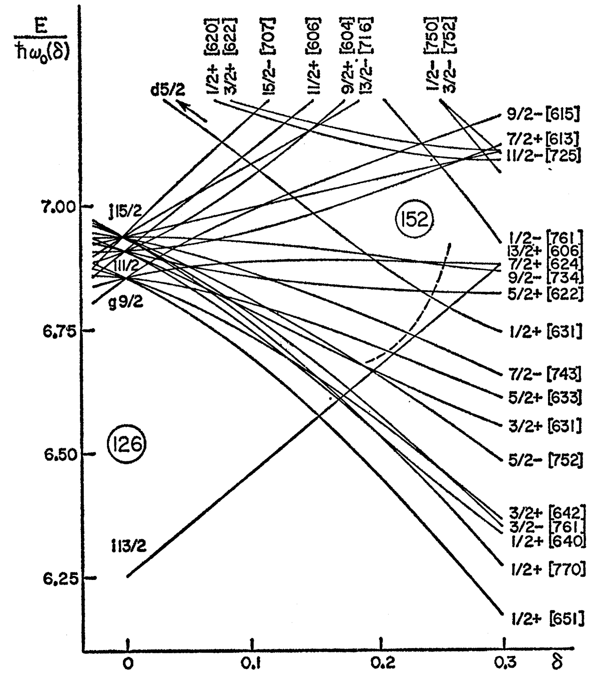

FIG. 6. Nilsson diagram for neutron numbers between 126 and 160. The dashed line represents roughly the deformations thought to pertain to stable nuclei in this region, as drawn in reference 26.

B. Comparison with Theoretical Expectations

The theory of (d,p) reactions in deformed nuclei has been treated by Satchler and Sawicki.[2,13,14] In Satchler's notation,[15] the differential cross section may be written

$$\frac{d\sigma(\theta)}{d\omega}=\frac{2I_2+1}{2I_1+1}\sum_l S_l\phi_l(\theta), \tag{1}$$

where $\phi_l(\theta)$ is the intrinsic Butler single-particle cross section and

$$S_l=\sum_j \theta_{jl}^2, \tag{1a}$$

$$\theta_{jl}(K_1\Omega_1,K_2\Omega_2)=g(2I_1+1/2I_2+1)^{\frac{1}{2}}\times\langle I_2K_2|I_1j\mp K_1\Omega_2\pm\Omega_1\rangle\times\langle\phi_2|\phi_1\rangle c_{jl}(\Omega_2\pm\Omega_1), \tag{1b}$$

$$c_{Njl}(\Omega w\alpha)=\sum_\Lambda a_{Nl\Lambda}\langle l\tfrac{1}{2}\Lambda\Omega-\Lambda|j\Omega\rangle. \tag{1c}$$

[12] A. Ghiorso, S. G. Thompson, G. H. Higgins, B. G. Harvey, and G. T. Seaborg, Phys. Rev. **95**, 293 (1954).
[13] J. Sawicki, Nuclear Phys. **6**, 575 (1958).
[14] J. Sawicki and G. R. Satchler, Nuclear Phys. **7**, 289 (1958).
[15] Following the notation of J. B. French and B. J. Raz, Phys. Rev. **104**, 1411 (1956).

TABLE I. Comparison of the experimental peak differential cross sections obtained in the present work with those calculated using Eq. (2) assuming the state assignments shown. Other assumptions entering into the calculated estimates are discussed in Sec. IV.B. The approximate Q values given are for purposes of identification only.

Target	State Q value	State Assignment	Calc. $(d\sigma/d\omega)_{max}$	Exp. $(d\sigma/d\omega)_{max}$
U^{233}	4.5	$\frac{5}{2}+[633]$	0.05	0.01
U^{235}	4.3	$\frac{7}{2}-[743]$	0.008	<0.002
Pu^{239}	4.2	$\frac{1}{2}+[631]$	0.3	0.08
U^{233}	3.1	$\frac{1}{2}+[631]$	0.8	0.4
U^{235}	3.2	$\frac{1}{2}+[631]$	0.8	0.4
Th^{232}	2.5	$\frac{1}{2}+[631]$	1.0	0.6
U^{238}	2.5	$\frac{5}{2}+[622]$	0.3	0.2
U^{238}	2.5	$\frac{7}{2}+[624]$	0.1	
U^{233}	2.1	Mainly $\frac{1}{2}+[620]$	2.3	1.4
U^{235}	1.9	Mainly $\frac{1}{2}+[620]$	2.3	1.5
Pu^{239}	2.4	Mainly $\frac{1}{2}+[620]$	2.3	1.4
U^{238}	1.8	Mainly $\frac{1}{2}+[620]$	2.3	1.8
Th^{232}	1.4	Mainly $\frac{1}{2}+[620]$	2.6	2.3

Here the target and residual nuclear quantum numbers are designated by indices 1 and 2. The usual notation of the unified model is used: ϕ_i represents the vibrational part of the wave function and $a_{Nl\Lambda}$ are the (normalized) coefficients calculated by Nilsson.[8] The captured nucleon is referred to by j and l, and g is $\sqrt{2}$ if either $K_1=\Omega_1=0$ or $K_2=\Omega_2=0$, and unity otherwise.

The approximation $\langle\phi_2|\phi_1\rangle\approx 1$ will be used for convenience (see reference 2). In the present work the different members of the rotational band have not been resolved and thus no comparison of the experimental results with Eq. (1) can be attempted.

If only the sum of the cross section over the rotational band of a nucleus with an even proton number is considered, the simpler expression obtained is

$$d\sigma(\theta)/d\omega = h\sum_{l\Lambda} a_{Nl\Lambda}{}^2\phi_l. \tag{2}$$

The following situations are relevant in the present investigation:

(a) Target even: $K_1=0$; $h=2$.
(b) Target odd: $K_1=0$. Summation over ground state band, $K_2=0$; $h=1$.
(c) Target odd: Summation over both bands with possible K_2; $h=2$.

Thus, for a particular single-particle state the contribution to the cross section of a certain l-value is given by the Nilsson coefficient, whereas the distribution of this cross section to the different members of the rotational band is given by the more complex Eq. (1).

In order to give a more quantitative basis for the interpretations in Sec. IV.A, estimates of some cross sections are attempted using Eq. (2). Of special interest is the cross section of the transition to the U^{236} ground state. The difficult part in this procedure is to estimate ϕ_l. The comparison is made for the maxima of the differential cross sections, using those obtained in previous investigations[4,5] in the lead region at the same deuteron energy. The variation of the cross section with Q is empirically estimated. Complete angular distributions were not taken, and thus the errors in the experimental data are large. The best agreement can be expected for relative comparisons in the same Q range.

The result is shown in Table I. The relative agreement is fair, which gives further support to the interpretations in Sec. IV.A. The experimental cross sections are small by about a factor of 2, which is in the right direction, since the Coulomb barrier is larger in the uranium than in the lead region. In the case of the even-even ground states, where a strong correlation exists between the particles, a factor of 4 is observed instead.

It is satisfying to note that the expected cross section of the U^{236} ground-state transition is very small. The calculated maximal differential cross section is only 8 μb/sr.

Cross sections have been calculated for all bound states. Above the gap at $N=152$ there is expected to be a group of states with relatively high cross sections (highest for $\frac{1}{2}+[620]$, $N=155$), followed by a number of states with smaller cross sections. It has been assumed in Table I that the large peak with $Q\sim 2$ Mev represents this group of states. However, at higher excitation no interpretation is suggested because of the uncertainties in the calculated excitation energies.

C. Neutron Binding Energies

Precise reaction Q values are of importance for the determination of nuclear masses. In the translead region only a few Q values with relatively large errors have been measured previously. Thus the published tables of nuclear masses[16–19] covering this region are based mainly on the decay energies in the four natural radioactive decay series. The energy differences between the series are determined through nuclear reactions in various lead isotopes. In this procedure the error in the masses becomes cumulatively larger as one proceeds towards higher masses. Therefore, Q values in the uranium region would be very useful in improving the mass tables by closed cycle calculations.

Unfortunately, the present rather accurate Q values are not as useful as could be hoped for because it is not certain that the highest Q value in a reaction represents the transition to the ground state. Either the ground-state transition may not have been observed at all or the ground state may not have been resolved from

[16] R. A. Glass, S. G. Thompson, and G. T. Seaborg, J. Inorgan. & Nuclear Chem. 1, 3 (1955).
[17] J. R. Huizenga, Physica 21, 410 (1955).
[18] B. M. Foreman, Jr., and G. T. Seaborg, J. Inorgan. & Nuclear Chem. 7, 305 (1958).
[19] F. Everling, L. A. König, J. H. E. Mattauch, and A. H. Wapstra, Nuclear Phys. 18, 529 (1960).

TABLE II. Q values and neutron binding energies obtained from the present experiment. The Q value listed is that of the most energetic proton group observed in each case, but in U^{235} and probably in Th^{232} this group does not represent the ground state. The neutron binding energies listed are corrected for estimated contributions to the observed group from more than one member of the ground-state rotational band, as described in the text. Errors quoted for the binding energies include the rms deviation, estimated systematic error, and error in the correction for low excited states.

Target	Measured Q value (Mev)	Rms deviation (Mev)	Corrected binding energy (Mev)	Error in binding energy (Mev)
Th^{232}	2.55	±0.03	...	...
U^{233}	4.52	±0.03	6.83	±0.11
U^{235}	3.20	±0.02	...	...
U^{238}	2.46	±0.02	4.74	±0.06
Pu^{239}	4.24	±0.03	6.49	±0.05

states of low excitation. Groups seen in (d,p) reactions corresponding to low excited states either can have a different single-particle configuration from the ground state, or can belong to the ground-state rotational band. In even nuclei the former type of excited states do not occur below an excitation of about 1 Mev. It is thus easy to decide whether the ground-state rotational band has been observed when the target is odd. The U^{233} and Pu^{239} Q values agree within 0.1 Mev with those derived from the mass tables and therefore the corresponding proton groups must be attributed to the ground-state rotational bands. The U^{235} Q value is 1 Mev smaller than expected, so that the U^{236} ground state was not observed. In Sec. IV.B this has been shown to be due to the fact that the U^{235} ground-state configuration is $\frac{7}{2}-[743]$.

Because the over-all experimental resolution was about 200 kev, the different members of the ground-state rotational bands were not resolved. The only way to correct for the fact that low excited states may have contributed to the observed proton groups is to calculate the cross sections using Eq. (1). The accuracy of this equation even in estimating cross sections has not been experimentally determined in heavy nuclei, although in Sec. IV.B fair agreement is obtained for relative cross sections when the sum over the rotational bands is considered. Thus it seems necessary to set the error in the correction about equal to the correction itself. The result of such a calculation is that in Pu^{240} the 0+ and 2+ states are predominantly excited, but in U^{234} the 4+ and 6+ states also contribute an appreciable cross section. The calculated corrections are 0.02 and 0.09 Mev, respectively.

When the target nucleus is even, the situation is complicated by the fact that bands of a configuration different from that of the ground state can occur at low excitation. The U^{239} ground-state configuration is expected to be $\frac{5}{2}+[622]$ from the Nilsson model. Expected states close to this are $\frac{7}{2}+[624]$ and $9/2-[734]$. Thereafter follows the gap at $N=152$. Pu^{241} (differing only by a proton pair from U^{239}) has a $\frac{5}{2}+[622]$ ground state, and $\frac{7}{2}+[624]$ is found at 172-kev excitation. In Cm^{245}, $9/2-[734]$ is well above $\frac{7}{2}+[624]$. It therefore seems likely that $\frac{5}{2}+[622]$ is the ground state of U^{239}. The ft value of the U^{239} β decay is consistent with this assignment. This state is expected to exhibit a cross section which is a factor of three larger than that of $\frac{7}{2}+[624]$. A calculation of the cross sections of the different members in the rotational band gives appreciable cross sections only for the $\frac{5}{2}+$ and $9/2+$ states. This calculation results in a correction of 0.05 Mev.

No conclusive evidence exists about the Th^{233} ground state assignment, and no previous experimental information is available regarding excited states in this nucleus. The ground state of Pu^{237} and U^{235} is $\frac{7}{2}-[743]$, and this is likely also for Th^{233}. Another possibility is $\frac{1}{2}+[631]$ which is found at an excitation of 145 kev in Pu^{237} and within 100 ev from the ground state of U^{235}. The Th^{233} ground-state beta decays primarily to the Pa^{233} ground state. This is consistent with a Th^{233} assignment of $\frac{1}{2}+[631]$ but not with $\frac{7}{2}-[743]$. However, there is also evidence of a small branching to the $\frac{5}{2}+[642]$ excited state in Pa^{233}, which is inconsistent with the $\frac{1}{2}+[631]$ assignment.[20] In Sec. IV.A the highest energy ($Q=2.55$ Mev) group observed in the $Th^{232}(d,p)$ reaction was given the $\frac{1}{2}+[631]$ assignment as a result of its large cross section. The binding energy corresponding to this group is then 4.78±0.03 Mev.[21] Because of the mentioned uncertainties in the Th^{233} ground state assignment, no definite conclusion can be drawn as to whether or not this group represents the ground-state transition. However, in the $Th^{232}(n,\gamma)$ reaction a gamma ray of 4.92±0.03 Mev is found.[22]

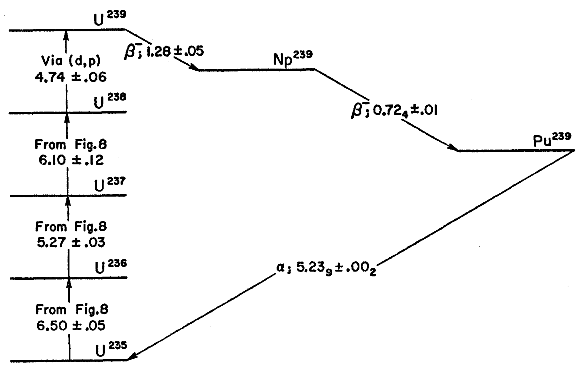

FIG. 7. Closed-energy cycle including neutron binding energies obtained in the present experiment.

[20] A Th^{233} ground-state spin of $\frac{3}{2}$- is consistent with both the β-decay and the (n,γ) results, but no such state is expected for $N=143$ from the Nilsson model.

[21] The correction for excitation of rotational states in the $\frac{1}{2}+[631]$ band is less than 0.01 Mev.

[22] L. V. Groshev, V. N. Lutsenko, A. M. Demidov, and V. I. Pelekhov, *Atlas of γ-ray Spectra from Radioactive Capture of Thermal Neutrons*, translated by J. B. Sykes (Pergamon Press, New York, 1959).

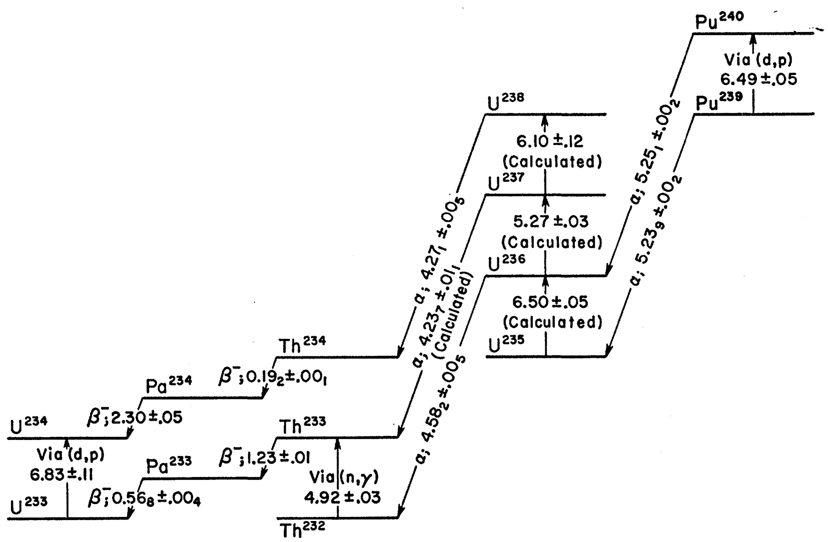

FIG. 8. Summary of available information on neutron binding energies in the uranium region, including the results of the present work labeled "Via (d,p)."

Thus the $Q=2.55$ Mev group appears to represent an excited state.[23]

The measured Q values and the corrected neutron binding energies derived from them are shown in Table II. The consistency of the binding energies obtained can be tested by means of the closed-energy cycle in Fig. 7. Only the binding energy in U^{239} was obtained directly, whereas the other binding energies have to be transformed as shown in Fig. 8.[24] The binding energy of four neutrons in U^{239} is (from the right branch in Fig. 7) 22.62 ± 0.05 Mev. The experimental result is 22.61 ± 0.15 Mev.

Because of the uncertainties in the interpretation of the data it is difficult to suggest any improvement in the existing mass tables. The most recent compilation[19] gives a Pu^{239} Q value of 4.16 Mev. The comparatively small error in the present corrected Q value of 4.26 Mev might indicate an error in either the $4n$ or $4n+3$ mass chain (or both). An increase in the $4n$ chain of 0.1 Mev would give agreement for the Pu^{240} binding energies and give better agreement for Th^{233}. A weak link in the $4n$ chain could be the Q_{β^-} of Ac^{228}. The value obtained by Bjørnholm *et al.*[25] is 0.10 Mev smaller than that used by Everling *et al.*[19]

Note added in proof. A reinvestigation of the $Th^{232}(d,p)$ proton spectrum using an overall resolution of about 100 kev has been made with improved targets recently available. The observed spectrum contains indications of a weak proton group at an energy corresponding to a binding of about 4.9 Mev, which adds support to the tentative conclusion of Sec. IVC that the $Q=2.55$-Mev group represents an excited state.

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[23] Whether the 4.92 Mev γ ray goes to the ground state is uncertain. An indication against such an interpretation is that the deviation from the binding energy of 5.07 Mev obtained from the mass table of reference 19 is rather large. Arguments in favor of this interpretation are: (1) A binding energy of 4.92 Mev is consistent with the binding energies determined in the present work as shown in Figs. 7 and 8. (2) A small proton peak is more likely to escape unobserved at a binding of 4.92 Mev which is at the high-energy side of the $Q=2.55$ Mev peak than at a binding of 5.07 Mev where only the background can obscure it.

[24] Since it is believed that the ground state was not observed in the $Th^{232}(d,p)$ reaction, the $Th^{232}(n,\gamma)$ value mentioned above was used.

[25] S. Bjørnholm, O. Nathan, O. B. Nielsen, and R. K. Sheline, Nuclear Phys. 4, 313 (1957).

[26] F. S. Stephens, F. Asaro, and I. Perlman, Phys. Rev. **113**, 212 (1959).