Neutron Binding Energies from (d,p) Q Values*†

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(Received July 9, 1954)

The Q values for the (d,p) reactions on some 27 targets whose neutron numbers are around the closed shells of 50 and 82 neutrons were determined. The general interpretation of these results and the specific application of these results to a variety of problems is discussed. In general, the results show a break of approximately 2 Mev at each of the shell edges. The technique used was that of a NaI scintillation spectrometer and is described in some detail. Comparison is also made with previous measurements by different techniques.

I. INTRODUCTION

THE binding energy of the last neutron B_n in many nuclei is known from experimental data such as (d,p) reaction Q values,[1] (γ,n) thresholds,[2] (n,γ) experiments,[3] and radioactive decay energies.[4] Much of this information is contained in the excellent summaries of Way[5] and Feather.[6] Despite the large amount of data represented in these compilations, one notices that there are regions of the periodic table where there is a paucity of information, particularly in the vicinity of nuclei with 82 or more neutrons. With this in mind, it was decided to study a number of (d,p) reactions in order to obtain additional values of B_n. From a study of (d,p) reactions one can also find the mass differences between various nuclei, the location of excited states, and other information. Following a brief discussion of the experimental technique, the results and their interpretations will be presented.

II. APPARATUS AND EXPERIMENTAL PROCEDURE

A. Emergent Beam and Electronic Equipment

The experiments reported here were performed using the M.I.T. cyclotron as a source of 15.1-Mev deuterons. The beam focusing arrangement, as well as many features of the scattering chamber, have been described in detail elsewhere.[7] The major experimental difference between the present experiments and those of Harvey,[1] using the same general apparatus, was in the energy measurement technique. Whereas his techniques involved the use of range-energy measurements, the present experiments used a NaI scintillation spectrometer in combination with an absorber of sufficient thickness to stop elastically scattered deuterons.

The scintillation spectrometer was essentially that described by Stoddart and Gove,[8] except that an RCA 6199 rather than an RCA 5819 photomultiplier was used. The high-voltage supply for the photomultiplier was the same as the one described by Higinbotham[9] and was stable enough to cause no fluctuations greater than 10 kev equivalent of the 10–15 Mev proton energy loss in the NaI crystal. The output of the photomultiplier drove a cathode follower adjacent to it. The cathode follower signal was then brought out of the scattering chamber through a vacuum seal and into a highly stabilized inverter and another cathode follower preamplifier. This preamplifier fed the 50-foot cable carrying the signal from the scattering chamber room, through the concrete shielding, to the electronic equipment area outside. The signal was then amplified by a linear amplifier designed by Hugh F. Stoddart of the M.I.T. cyclotron group. The basis for this amplifier was the non-overloading amplifier described by Chase and Higinbotham.[10]

Pulse-height measurements were made with a single-channel analyzer of the type described by Johnstone.[11] External biasing was used so that the bias could be "stepped" automatically. The same stepping arrangement which changed the bias caused the differential pulse-height scaling circuit output to go into an appropriate register. The stepping relays performing these actions were actuated by the beam monitor reaching a predetermined number of counts.[12] The monitor consisted of another scintillation counter which could could either see the same area of the target as the spectrometer, or could be placed in such a position so as to see the elastically scattered deuterons from a thin gold foil near the beam catcher. In either case, the entire beam target area was seen by the spectrometer and the monitor. The output of the monitor counter was scanned with an integral discriminator and then

* This work is based in part on material submitted in partial fulfillment for the Ph.D. degree at Massachusetts Institute of Technology.

† This work was supported in part by a joint program of the U. S. Office of Naval research and the U. S. Atomic Energy Commission.

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[1] J. A. Harvey, Phys. Rev. **81**, 353 (1951).
[2] Sher, Halpern, and Mann, Phys. Rev. **84**, 387 (1951).
[3] Kinsey, Bartholomew, and Walker, Phys. Rev. **78**, 77, 481 (1950); Canadian J. Phys. **31**, 1025 (1953).
[4] A. H. Wapstra, thesis, University of Amsterdam, 1953 (unpublished).
[5] K. Way (private communication).
[6] N. Feather, Phil. Mag. Supplement **2**, 141 (1953).
[7] Boyer, Gane, Harvey, Deutsch, and Livingston, Rev. Sci. Instr. **22**, 310 (1951).
[8] H. F. Stoddart and H. E. Gove, Phys. Rev. **87**, 262 (1952).
[9] W. A. Higinbotham, Rev. Sci. Instr. **22**, 429 (1951).
[10] R. Chase and W. A. Higinbotham, Rev. Sci. Instr. **23**, 34 (1952).
[11] C. W. Johnstone, Nucleonics **11**, 36 (1953).
[12] M.I.T. Laboratory for Nuclear Science Progress Report, November 30, 1952 (unpublished).

set below the pulse height corresponding to elastic deuterons. The discriminator could be varied over a large range without significant changes in the counting rate; that is to say, the monitor was insensitive to small changes in energy or amplification.

The various scaling circuits used are those described in reference 7.

B. Targets

For most of the nuclei studied in these experiments, thin (10–20 mg/cm^2) metallic or elemental foils could not be obtained easily. In addition, since it was desired to study a large number of separated isotopes,[13] it was necessary to have the targets in a readily recoverable form. Therefore, a compound of the element to be studied containing only carbon, hydrogen, or oxygen was ground to a fine powder and mixed with a solution of polystyrene dissolved in benzene. This slurry was then spread onto a glass plate and allowed to dry at room temperature. The resulting foil could then be peeled off the glass with a razor blade.[14]

The reason for using only compounds of carbon, hydrogen, or oxygen lies in the fact that these elements are practically monoisotopic and the abundant isotopes have ground-state Q values lower than most of the nuclei studied. In addition, these nuclei are lighter than any of those studied so that the proton groups corresponding to levels of the same Q value, of the elements studied, had higher energy in the laboratory frame of reference.

C. Q-Value Determinations

The ratio of the pulse heights corresponding to the maxima of the spectra of the clearly resolved ground and first excited states of C^{13} was measured in order to determine the beam energy as well as the relationship between energy and pulse height rapidly and precisely.[15] By assuming a set of beam energies and calculating this ratio by means of the Q equation for each assumed energy, one could find the ratio corresponding to the actual beam energy. Then, knowing the beam energy as well as the target thickness, angle of counter, and absorber thickness, one can calculate the energy lost in the crystal by the ground-state proton group. The absorber thickness as well as the other factors just mentioned are also considered in ratio calculation.

The actual analysis of the pulse-height data is carried out in the following manner. From the pulse-height measurement we can find the proton energy loss in the NaI crystal. With the range-energy curves of Smith[16] as modified by Harvey[1] it is possible to calculate the proton energy when the particles leave the target. Then, using the relative stopping powers as measured by Harvey[1] and knowing the deuteron beam energy, one can calculate both the proton and deuteron energies at the center of the target. Knowing these particle energies at the centers of both targets, one can calculate the unknown Q value relative to that of a reference target, from the equation

$$Q_x-Q_r=(E_{p_x}-E_{p_r})-(E_{d_x}-E_{d_r})+\frac{(E_{p_x}+2E_{d_x})}{A_x}-\frac{(E_{p_r}+2E_{d_r})}{A_r}-2\left[\frac{(2E_{p_x}E_{d_x})^{\frac{1}{2}}\cos\theta_x}{A_x}-\frac{(2E_{p_r}E_{d_r})^{\frac{1}{2}}\cos\theta_r}{A_r}\right],$$

where E_p and E_d refer to proton and deuteron energies, the subscripts x and r refer to the unknown and known Q-value groups, respectively, A is the mass of the residual nucleus, and θ is the angle of the detector with the incident beam.

In order to minimize the effect of any systematic errors, the present measurements were made by comparing the proton groups from the nucleus under consideration to a proton group corresponding to a reaction of well-known Q value.[1] Frequently this was the C^{13} end group from the $C^{12}(d,p)C^{13}$ reaction in either the target polystyrene or, usually, the same polyethylene target used to measure the beam energy. A consideration of possible causes of systematic errors leads one to believe they introduce no significant error in the final result, at least to the accuracy of these experiments.[17]

On the other hand, when one considers other sources of error,—that is, errors which affect the unknown Q-value proton group differently from the reference group, one finds as the largest single factor the inability to locate accurately the maximum of the spectrum. This difficulty in locating spectral maxima is due directly to the over-all poor energy resolution of the technique used. When one considers effects such as photomultiplier statistics and energy straggling in the absorber, one sees that the energy spread of a clearly resolved proton group is about 500–600 kev (full width at half-maximum) for the targets used. Consequently, errors as large as 200–300 kev can be introduced in the location of the energy of the proton group under consideration. Figure 1 illustrates the over-all resolution of this setup for the ground-state proton group from C^{13}.

The other main source of error in these measurements is the error in target thickness. The thickness is measured by comparing the energy of the proton groups from the C^{13} ground state reaction in the target to those coming from the reference target. Since we are measuring a small difference between two large quantities, the technique is somewhat insensitive. However, it is

[13] These isotopes were supplied by the Staple Isotopes Division, Oak Ridge National Laboratory.

[14] N. S. Wall and J. W. Irvine, Jr., Rev. Sci. Instr. (to be published).

[15] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).

[16] J. H. Smith, Phys. Rev. **71**, 39 (1947).

[17] N. S. Wall, Ph.D. thesis, Massachusetts Institute of Technology, October, 1953 (unpublished).

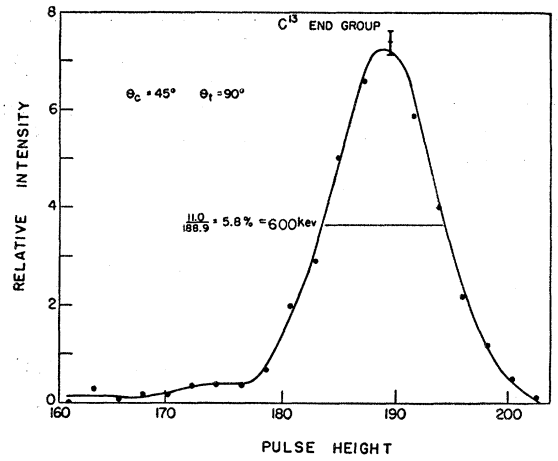

FIG. 1. Spectrum of $C^{12}(d,p)C^{13}$ ground-state to ground-state reaction. The abscissa is given in terms of absolute pulse height as determined by a precision pulser.

believed no errors of greater than 50 kev are introduced in this manner. The best criterion of the errors in these experiments is, however, a comparison between the present results and other measurements; for example, Sr^{89}, Sn^{121}, and Bi^{210}.

III. RESULTS

The experimental results of the ground state Q-value determinations are given in Table I. The location of any excited states that could be resolved are listed in the third column of this table. In most cases, these excitation energies were determined using the equation given above with the ground-state Q value as the reference. For the energy of particles, and the heavy nuclei examined here, the excitation energy is practically equal to the difference of the outgoing proton energies corresponding to the ground-state and excited-state proton groups.

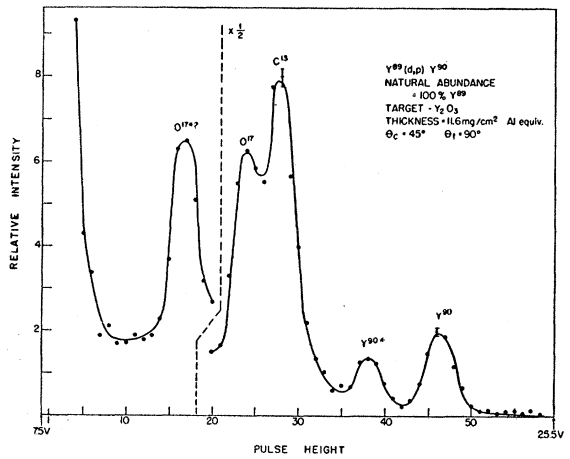

FIG. 2. The $Y^{89}(d,p)Y^{90}$ spectrum. The abscissa in this figure as well as Figs. 3 and 4 is given in arbitrary pulse heights. The absolute pulse heights can be found from the notations at either border indicating the pulse height in volts.

Figures 2–4 show the proton spectra from several typical targets. Figure 2 shows the clearly resolved end group and first excited states from a thin, uniform Y_2O_3 in polystyrene target. Figure 3 shows the analysis necessary to interpret the spectrum and derive the ground-state Q value for the $Ce^{140}(d,p)Ce^{141}$ reaction. Since the Q value as determined here is only about 450 kev higher than the C^{13} Q value, and C^{12} is probably present to a much higher concentration in the target, the Ce^{141} end proton group is on the high-energy side of the C^{13} end group and not clearly resolved from it. The graphical analysis was based on an analysis of the different causes of spread such as energy straggling, and the energy dependence.[17] Figure 4 shows the spectrum from the reaction $Mo^{92}(d,p)Mo^{93}$. This target was a suspension of MoO_3, enriched to about 87 percent Mo^{92}, in polystyrene. The spectrum again illustrates

TABLE I. Experimental results.

Residual nucleus	Q value of ground state reaction Mev	Excitation energies Mev
Ca^{49}	2.80±0.30	
Sr^{85}	5.25±0.30	
Sr^{87}	6.26±0.20	
Sr^{89}	4.29±0.15	
	3.20±0.20	1.09
Rb^{86}	6.2 ±0.3(?)	
		1.5(?)
Rb^{88}	3.75±0.20	
Y^{90}	4.41±0.05	
		1.17±0.06
Zr^{93}	4.46±0.05	
Mo^{93}	5.63±0.05	
		0.91±0.10
		1.41±0.10
		2.23±0.10
		2.73±0.10
Zr^{95}	4.19±0.05	
		0.9 ±0.2
Mo^{97}	4.51±0.30	
Mo^{98}	6.06±0.10	
		2.5 ±0.3
Cd^{113}	4.10±0.09	
		0.55±0.08
Cd^{115}	$3.52^{+0.15}_{-0.06}$	
Sn^{121}	3.92±0.07	
Sn^{125}	3.52±0.07	
		1.16±0.08
		2.77±0.10
		3.41±0.10
		4.09±0.10
Te^{125}	4.25±0.07	
Te^{126}(?)	5.0 ±0.2	
I^{128}	4.35±0.05	
Cs^{134}	4.50±0.10	
La^{140}	2.87±0.10	
Ce^{141}	3.17±0.10	
Ce^{143}	2.86±0.07	
		0.90±0.15
Pr^{142}	3.42±0.30	
		0.62±0.10
Nd^{143}	3.79±0.08	
		0.70±0.10
Sm^{155}	3.36±0.30	
Bi^{210}	1.94±0.03	

the difficulties in resolving single levels, although in this particular reaction the end group is clearly resolved.

For some of the targets studied the end proton group was resolved even more poorly than the Ce^{141}. This was attributed to poor targets (i.e., too thick or not sufficiently uniform), or low-lying levels. In other cases, however, the end groups were resolved more clearly than the Y^{90} ground-state group.

Table II lists the binding energy of the last neutron in each of the nuclei studied, as well as comparisons of these measurements with measurements made by means of other techniques and reactions. In particular, the

TABLE II. Neutron binding energies in Mev and comparison with Metropolis-Reitwiesner predictions.

Nucleus	B_n (obs)	B_n (calc)	B_n (obs) $-B_n$ (calc)	Other measurements	Ref.
$_{20}Ca^{49}$	5.0	4.1	+0.8		
$_{38}Sr^{85}$	7.48	7.92	−0.4		
$_{38}Sr^{87}$	8.49	7.18	+1.3	(n,γ) 8.42 (d,p) 8.52±0.20	a b
$_{38}Sr^{89}$	6.52	6.53	0	(d,p) 6.55±0.10 (d,p) 6.55±0.20	c b
$_{37}Rb^{86}$	8.4	6.8	+1.6		
$_{37}Rb^{88}$	5.98	6.12	−0.1		
$_{39}Y^{90}$	6.64	7.06	−0.4		
$_{40}Zr^{93}$	6.69	6.88	−0.2	(d,p) 6.56±0.10	b
$_{42}Mo$	7.86	8.47	−0.6	(d,p) 8.31±0.2	b
$_{40}Zr^{95}$	6.42	6.28	+0.1		
$_{42}Mo^{97}$	6.7	7.2	−0.5	(γ,n) 7.1 ±0.3	d
$_{42}Mo^{98}$	8.29	9.04	−0.8		
$_{48}Cd^{113}$	6.33	6.83	−0.5	(γ,n) 6.44±0.15	e
$_{48}Cd^{115}$	5.75	6.36	−0.6		
$_{50}Sn^{121}$	6.15	6.17	0	(d,p) 6.2 ±0.3	b
$_{50}Sn^{125}$	5.75	5.33	+0.4		
$_{52}Te^{125}$	6.48	6.47	0	(γ,n) 6.50±0.2	e
$_{52}Te^{126}$?	7.2	8.1	−0.9		
$_{53}I^{128}$	6.58	6.33	+0.3		
$_{55}Cs^{134}$	6.73	6.16	+0.6		
$_{57}La^{140}$	5.10	6.00	−0.9		
$_{58}Ce^{141}$	5.40	6.30	−0.9		
$_{58}Ce^{143}$	5.09	5.93	−0.9		
$_{59}Pr^{142}$	5.65	6.60	−1.0		
$_{60}Nd^{143}$	5.02	5.89	−0.9		
$_{62}Sm^{155}$	5.58	5.69	−0.1		
$_{83}Bi^{210}$	4.17	5.82	−1.7	(n,γ) 4.17±0.015 (d,p) 4.14±0.03	a b

[a] See reference 3.
[b] See reference 1.
[c] See F. B. Shull and C. E. McFarland, Phys. Rev. **89**, 489 (1953).
[d] See reference 33.
[e] See reference 2.

measurements on Te^{125}, Cd^{113}, and Mo^{97} should be noticed. The measurements given in the last column of Table II are all of such a nature that they would set an upper limit on the neutron binding energy (6).[18,19] On the other hand, since the ground-state proton group may not have been observed, the (d,p) reaction only leads to a lower limit on the neutron binding energy. (From conservation of energy the binding energy of the last neutron equals the Q value of the ground-state to

[18] The measurement on Mo^{97} was made by using the Cu^{63} threshold as 10.9 Mev. The recent re-evaluation of this to 10.6 Mev (see reference 19) would make the (γ,n) and (d,p) agreement very close.

[19] Birnbaum, Harth, Seren, and Tobin, Phys. Rev. **91**, 474(A) (1953).

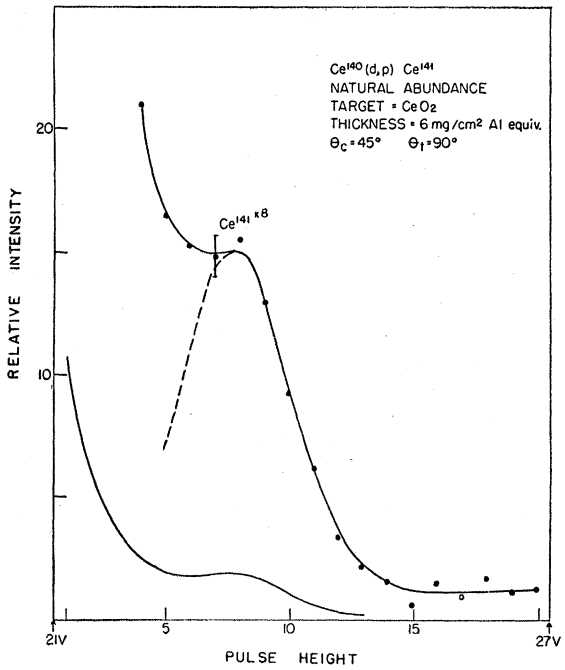

FIG. 3. The $Ce^{140}(d,p)Ce^{141}$ spectrum. See Fig. 3 for explanation of abscissa.

ground-state (d,p) reaction plus the binding energy of the deuteron, 2.23 Mev.) It is therefore worth noting the agreement between these two methods as it lends confidence to the general approach of deriving binding energies from either (d,p) or (γ,n) reactions. Table II also lists the binding energy expected on the basis of the semiempirical mass formula.[20,21]

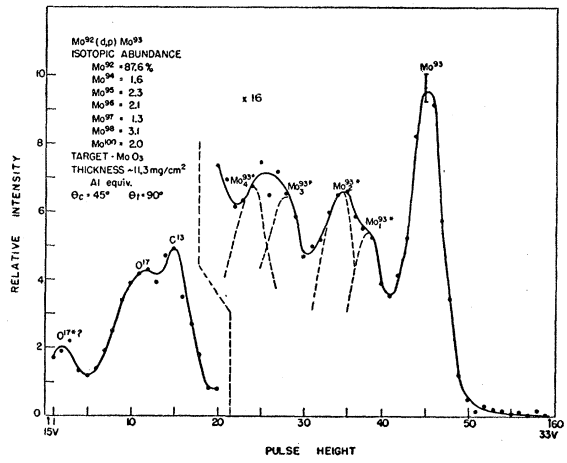

FIG. 4. The $Mo^{92}(d,p)Mo^{93}$ spectrum. See Fig. 2 for explanation of abscissa.

[20] R. Metropolis and G. Reitwiesner, Atomic Energy Commission Report NP-1980, 1950 (unpublished).

[21] E. Fermi, *Nuclear Physics* (University of Chicago Press, Chicago, 1950).

IV. DISCUSSION

A. Relationship to Shell Model

In general, the results in Tables I and II show the same effect at shell edges as the measurements of Harvey[1] and those of Sher *et al.*[2] That is, at the "magic" numbers of 50 or 82 neutrons there is pronounced decrease in the binding energy of the last neutron.[22] There is now, however, more data available at each of these shells than before. These data are shown in Fig. 5. This plot shows the measured values of B_n minus the value of B_n expected on the basis of the semiempirical mass formula[20] as a function of the neutron number. No values are plotted which are based on the indirect determination of B_n from, for example, decay data. The main content of this plot is based upon references 1, 2, and 3 and the present work; however, other sources of data have been used.[23]

From this plot one can see that at the 50 and 82 shells there is a break of about 2.0–2.3 Mev in B_n-B_n (calc). This break is similar to the one at 126 neutrons.[1] It should be pointed out, however, that at none of the shells is this break *directly* related to the strength of the spin-orbit coupling since the level filled just after the magic number is not a member of the same doublet filled at or just before it. In order to evaluate any spin-orbit parameter one would therefore have to know the order of the levels before a spin-orbit perturbation is introduced. This in turn is related to a particular nuclear model.

In Fig. 5 there are three points just prior to $N=50$ representing B_n for Sr^{85}, Kr^{85},[24] and Sr^{86}.[2] These values

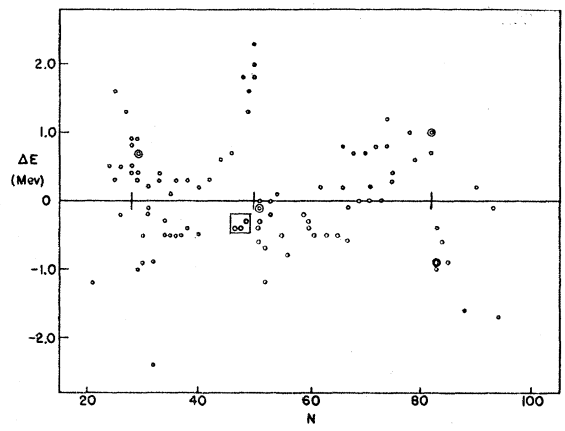

FIG. 5. The binding energy of the last neutron minus the binding energy expected on the basis of the semiempirical mass formula as a function of the neutron number of the target nucleus. The double circles indicate two nuclei with the same value of ΔE, and the heavy circle indicates three nuclei with the same value of ΔE. The three nuclei enclosed in the box are doubtful measurements and are discussed in Sec. IV-A of the text.

are in pronounced disagreement with other nuclei in this general vicinity.

Sr^{85}.—The Sr^{85} measurement reported here may be low due to the fact that the targets used in these experiments had only about 45 percent Sr^{84} and about 15 percent Sr^{86}. B_n for Sr^{85} should be somewhat higher than B_n for Sr^{87}, since Sr^{85} has a smaller neutron excess. If for some reason the intensity of the Sr^{85} ground-state proton group was less than the intensity of the Sr^{87} group, then it may have escaped observation.

Sr^{86}.—The B_n for Sr^{86} again should be somewhat higher than that of Sr^{88}. Since Sr^{86} is present in only low abundance in natural Sr, the neutrons corresponding to the (γ,n) reaction on Sr^{86} may have been missed in the measurements of Sher *et al.*[2]

Kr^{85}.—With respect to Kr^{85}, Wheeler *et al.* mention that the actual binding energy may be some 0.9 Mev higher, but feel that it is unlikely. However, even with a B_n 0.9 Mev higher B_n-B_n (calc) would still be low as compared to other nuclei in this region.

Relative to the shell model, it should be pointed out that $B_n(Ca^{49})$ does not show the effect of either neutron number 28 or proton number 20. This is similar to the cases of V^{52} and Fe^{55},[1] but a behavior unlike that of the Ti isotopes as analyzed by Pieper.[23] However, when Pieper's data is compared to the mass formula, no "magic effect" is observed. (See Fig. 5.)

It should also be noted that of the nuclei referred to in Fig. 5 in the region around $N=35$, those lying above the B_n-B_n (calc)$=0$ line are mostly even-A nuclei, whereas those below the line are odd-A nuclei. This may be entirely a result of the fact that the mass formula[21] pairing term $\delta/A^{\frac{3}{4}}$ is poorly estimated in this mass region.

B. Double β Decay

As has been pointed out in an earlier paper[25] the neutron binding energies for Te^{125} and Sn^{125} along with the decay energies of Sn^{125} and Sb^{125} allow one to conclude that there is 2.4 ± 0.3 Mev available for the double β decay of Sn^{124}. In a similar fashion one can show that there is at least 4.3 ± 0.3 Mev available for the decay of Ca^{48} to Ti^{48}. In this case, however, the decay energies are not known to sufficient accuracy[26] for the result to be meaningful even though it agrees with the mass spectroscopic data, 4.34 ± 0.11 Mev.[27]

C. Mo^{98}

On the basis of the compound nucleus theory of nuclear reactions, the neutron capture cross section of a particularly stable nucleus, such as the magic number nuclei, should be low as compared to a normal

[22] M. G. Mayer, Phys. Rev. **78**, 16 (1950); Haxel, Jensen, and Suess, Z. Physik **128**, 295 (1950).
[23] G. Pieper, Phys. Rev. **88**, 1299 (1952).
[24] Wheeler, Schwartz, and Watson, Phys. Rev. **92**, 121 (1953).
[25] N. S. Wall, Phys. Rev. **92**, 1526 (1953).
[26] Hollander, Pearlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).
[27] Collins, Nier, and Johnson, Phys. Rev. **86**, 407 (1952); **84**, 717 (1951).

nucleus.[28,29] Mo^{98}, as well as other nuclei with from 56–60 neutrons, shows an anomalously low capture cross section.[30] Mo^{98}, therefore, should show a particularly high binding energy for the last neutron, since Mo^{97} seems to be a normal nucleus compared to others in that region. (See Table II.) However, the binding energy of the last neutron is 8.29 Mev or compared to the mass formula the difference B_n-B_n (calc) is equal to -0.8 Mev. The average difference in this region of the periodic table is only about -0.4 Mev.

It may be that the last neutron in Mo^{99} is only very loosely bound relative to Mo^{98}. Then the neutron added to Mo^{98} would enter the compound nucleus in a region of low level density. However, at other magic numbers there is a relative increase of B_n-B_n (calc) just before the shell edge, whereas here none is observed. Consequently, the nuclei that show an anomalously low cross section, in this region of the periodic table, might do so for another reason, or the compound nucleus theory may be inadequate here.[31]

D. Bi^{210}

The Q value of the highest-energy proton group from the reaction $Bi^{209}(d,p)Bi^{210}$ has been measured and found to be 1.94 ± 0.03 Mev, in excellent agreement with Harvey[1] and Kinsey.[3] It is felt that this proton group does not truly represent the ground state of Bi^{210}, but several excited states of about 400–500-kev excitation too closely spaced to be resolved in the present experiments. The following paper on the angular distributions of the protons from the $Q=1.94$-Mev level will discuss this point in greater detail.

E. Sn^{125}, Mo^{93}, Y^{90}, Ce^{143}, Pr^{142}, Nd^{143}

These nuclei show excited states which, at least within the resolution of the present experiments, are clearly resolved and have a several hundred kilovolt spacing, for the first excited state, and in some cases higher levels.

Y^{90}, Pr^{142}, and Nd^{143} have one neutron over a closed shell, Ce^{143} has three, but Sn^{125} is not too close to either the 50 or 82 shells. On the other hand, Sn^{125} is proton magic and therefore, if the neutrons and protons are coupled as in the collective model,[31] one might expect such a level structure.

F. Cd^{113}

The ground state of Cd^{113} is believed to be unstable relative to In^{113}.[26] Because there is a large spin difference between the ground states of these nuclei, as well as a low but unknown energy difference, the lifetime for this decay should be quite long. An isomer in Cd^{113} is known to decay to the ground state of In^{113}, but the energy of excitation of this isomer is not known.[26] If it is assumed that the excited state found in these experiments is the same as the isomer then one can calculate the decay energy for the ground-state transition. From the data given in Table I and the Cd^{113m} decay energy,[32] the ground-state decay energy of Cd^{113} should be 0.04 ± 0.08 Mev.

G. Mo^{92}

On the basis of Harvey's measurement of $B_n(Mo^{93})$, Feather[6] has estimated Mo^{92} to be 0.08 ± 0.35 Mev capture-unstable to Nb^{92}. Using the value for B_n given in Table II, however, a similar calculation shows Nb^{92} is unstable to decay to Mo^{92} by 0.53 Mev.

H. Calculated Values of B_n

Though no measurements of the sort given below were used in Fig. 5, from appropriate total decay energies and known B_n values, B_n for other nuclei can be found. For example:

$$\begin{aligned} &Ce^{140}+n=Ce^{141}+B_n(Ce^{141}),\\ &Ce^{141}\overset{\beta}{=} Pr^{141}+E_{\beta 1},\\ &Pr^{141}=Pr^{140}+n-B_n(Pr^{141}),\\ &Pr^{140}\overset{\beta}{=} Ce^{140}+E_{\beta 2}. \end{aligned}$$

Adding these four equations and using the value 5.40 Mev given in Table II for $B_n(Ce^{141})$ as well as 0.58 Mev for $E_{\beta 1}$ and 3.25 Mev for $E_{\beta 2}$,[26] one finds $B_n(Pr^{141})=9.2\pm0.3$ Mev. This agrees quite nicely with the value 9.4 ± 0.3 Mev as given by Hanson.[33] This latter value should probably be lowered 0.3 Mev, however, since it was measured relative to a 10.9-Mev $Cu^{63}(\gamma,n)Cu^{62}$ threshold. See footnote in Sec. III.

Other values which can be determined in a similar manner are $B_n(Kr^{88})\leq 6.8$ Mev; $B_n(In^{113})=9.13$ Mev; $B_n(La^{141})=6.7$ Mev; and $B_n(Ba^{140})=6.32$ Mev.

The author would like to thank Mr. E. F. White and the M.I.T. cyclotron crew for valuable assistance in building and maintaining much of the equipment used in these experiments. He would also like to thank Mr. H. F. Stoddart for the design and construction of the major part of the electronic instrumentation. It is a pleasure to acknowledge many valuable conversations with Dr. H. E. Gove, Dr. Katherine Way, Dr. J. W. Irvine, Jr., and Dr. J. A. Harvey. A particular debt of gratitude is due Professor Martin Deutsch for the guidance, advice, and training the author received from him.

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