Atomic Masses in the Region from Iron to Zinc*

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The large double-focusing mass spectrometer recently constructed at this laboratory has been used to measure the atomic masses of the stable isotopes of iron, cobalt, nickel, copper, and zinc. Except in the cases of nickel and copper, the new masses agree reasonably well with the results of previous investigations.

The isotopic assignment of neutron capture γ rays in the above elements has been examined using the new data and several new (n,γ) reaction Q values result. Comparison between measured stable isotope mass differences and the mass differences calculated from nuclear disintegration energies shows no outstanding discrepancy in this region, assuming the new (n,γ) assignments to be correct.

From nuclear energy data a complete mass table has been calculated for these five elements and the resulting masses used to investigate nucleon binding energies. The binding energy of the last proton or last neutron in the nucleus shows a reasonably consistent variation with mass. Pairing energies for the last neutron and last proton pairs have also been calculated wherever sufficient mass data exist. Only partial correlation seems possible between pairing energy and the angular momentum of the level occupied by the pair.

INTRODUCTION

THE development of the large double-focusing mass spectrometer at the University of Minnesota makes possible the measurement of atomic masses with increased precision.[1–3] Because there have existed frequent discrepancies, not only between the results of the various mass spectroscopic investigations, but also between the spectroscopic masses and mass differences calculated from nuclear energy data, it seems desirable to re-examine with this instrument such regions of disagreement.

The region studied in the present investigation was chosen both because of the several disagreements between the mass spectrometric and nuclear energy data and because of certain unexplained breaks in the packing fraction curve. Recently others have discussed the discrepancies in this region[4–6] and they too suggest the possible existence of incorrect results. Many of the inconsistencies between the nuclear data and the mass results were discussed by Wapstra[7] in connection with his mass table calculation.

Besides helping to resolve these discrepancies, measurements made with the precision of the present spectrometer are useful in systematically investigating binding energies of nucleons. The measurements reported here have an accuracy of about 1 in 10 000 000, hence quantities such as the last nucleon binding energy may be calculated with useful precision.

The present measurements cover the stable isotopes of the elements iron, cobalt, nickel, copper, and zinc. Mass doublets sufficient to determine the masses of some of these have been measured previously,[8] though the only systematic study is that of Collins *et al.*[9] The mass of the stable isotope of cobalt has never before been measured.

MEASUREMENTS

The mass doublets which relate the masses of the isotopes in question to the masses of the secondary standards are listed in Table I together with their measured values. Each error quoted is the square root of the sum of the squares of (a) the statistical standard error of the mean associated with the set of runs of the doublet and (b) a factor reflecting the possible error in

TABLE I. Measured mass doublet differences (in mMU).

Doublet measured[a]	Number of runs	Mass difference[b]
$C_4H_6-Fe^{54}$	11	107.374 ±4
$C_4H_8-Fe^{56}$	14	127.698 ±4
$C_4H_9-Fe^{57}$	8	135.055 ±7
$C_4H_{10}-Fe^{58}$	6	144.977 ±4
$C_2H_3O_2-Co^{59}$	11	80.1466±23
$C_4H_{10}-Ni^{58}$	12	142.941 ±7
$C_2H_4O_2-Ni^{60}$	12	90.387 ±6
$C_2H_5O_2-Ni^{61}$	10	97.894 ±5
$C_5H_2-Ni^{62}$	10	87.339 ±6
SO_2-Ni^{64}	14	33.901 ±5
$C_5H_3-Cu^{63}$	17	93.909 ±7
$C_5H_5-Cu^{65}$	19	111.377 ±4
SO_2-Zn^{64}	15	32.7687±32
$O_2-\frac{1}{2}Zn^{64}$	14	25.2633±26
$C_5H_6-Zn^{66}$	14	120.935 ±6
$C_5H_7-Zn^{67}$	13	127.675 ±7
$C_5H_8-Zn^{68}$	13	137.781 ±4
$C_5H_{10}-Zn^{70}$	11	152.953 ±6

[a] Throughout this paper, H, C, O, and S refer to the abundant isotopes of these elements, namely H^1, C^{12}, O^{16}, and S^{32}.
[b] Errors are essentially standard error. See text for the method of calculation.

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[1] For a description of the instrument see Scolman, Quisenberry, Collins, Giese, and Nier (to be published).
[2] Quisenberry, Scolman, and Nier, Phys. Rev. **102**, 1071 (1956).
[3] Scolman, Quisenberry, and Nier, Phys. Rev. **102**, 1076 (1956).
[4] Kerr, Taylor, and Duckworth, Nature **176**, 458 (1955).
[5] Kerr, Isenor, and Duckworth, Z. Naturforsch. **10a**, 840 (1955).
[6] Eastman, Isenor, Bainbridge, and Duckworth (private communication, 1956).
[7] A. H. Wapstra, Physica **21**, 385 (1955).
[8] For a review of recent work see Duckworth, Hogg, and Pennington, Revs. Modern Phys. **26**, 463 (1954).
[9] Collins, Nier, and Johnson, Phys. Rev. **86**, 408 (1952).

TABLE II. Atomic masses of the stable isotopes of iron, cobalt, nickel, copper, and zinc.

Isotope	Mass (amu)[a]	Isotope	Mass (amu)[a]
Fe^{54}	53.956 758±5	Cu^{63}	62.949 607±8
Fe^{56}	55.952 722±4	Cu^{65}	64.948 427±5
Fe^{57}	56.953 509±7		
Fe^{58}	57.951 731±4	Zn^{64}	63.949 473±5[b]
			63.949 471±3[c]
Co^{59}	58.951 919±3	$(Zn^{64})_{Av}$	63.949 472±3
		Zn^{66}	65.947 013±7
Ni^{58}	57.953 767±7	Zn^{67}	66.948 418±7
Ni^{60}	59.949 823±6	Zn^{68}	67.946 456±5
Ni^{61}	60.950 460±5	Zn^{70}	69.947 572±6
Ni^{62}	61.948 033±7		
Ni^{64}	63.948 339±5		

[a] Errors are essentially standard errors. See text for the method of calculation.
[b] Calculated from the doublet $O_2-\frac{1}{2}Zn^{64}$, see Table I.
[c] Calculated from the doublet SO_2-Zn^{64}, see Table I.

the calibration of the spectrometer. This method of assigning errors assumes the nonexistence of systematic errors. Each run consists of a total of 20 measurements taken and analyzed in the manner previously described for use with this spectrometer.[2,3]

Ions are obtained by electron bombardment of molecular vapor in the ion source. Vapor for the reference members of the doublets was obtained from the appropriate liquid or gas. The metallic elements were vaporized directly in the ion source using an electrically heated metal boat.

MASSES

The atomic masses calculated from the doublets of Table I are listed in Table II together with their associated errors. The mass of Zn^{64} was measured using two different doublets and the final mass is the unweighted average of the two results. Agreement between the two is excellent, and in fact is somewhat better than might be expected. Errors given are standard errors, calculated by taking the square roots of the sums of the squares of the standard errors associated with the doublet results and with the reference ion masses. The reference ion masses may be calculated as combinations of CH_4, C_2H_4, and C_3H_8, as well as C and H. Thus the reference ion mass errors are derived from the errors associated with the measured results for the mass doublets CH_4-O, C_2H_4-CO, and $C_3H_8-CO_2$,[2] and hence are not directly calculable from the quoted secondary standard errors.

Values used for the secondary standards H^1, C^{12}, and S^{32} are those previously obtained by using this spectrometer.[2] They are $H^1=1.0081442\pm2$ amu, $C^{12}=12.0038167\pm8$, and $S^{32}=31.9822401\pm9$.

COMPARISON WITH MASS SPECTROSCOPIC RESULTS

In Table III the mass excesses $(M-A)$ measured in the present experiment are compared with the results of the previous systematic investigation.[9] An examination of the differences between the two sets (Δ = present mass excess minus previous mass excess) shows reasonably good agreement for the isotopes of iron and zinc, except Zn^{67} and Zn^{68}. However, in the cases of nickel and copper large discrepancies are noted. The general pattern is that the masses obtained previously for the isotopes of these latter elements appear to be low.

Recently mass spectrographic measurements have been made in this region by Duckworth's group at McMaster University.[5,6] Two of the doublets they measured are the same as those used here. These are presented in Table IV and compared with the present results. Both McMaster results are higher, although the Zn^{64} doublet is not inconsistent.

Several other zinc and nickel masses may be determined from the recent McMaster data. These too are compared with the present results in Table IV. The values of the secondary standards used in the present paper have been used to obtain masses from the McMaster doublets and in the cases of Zn^{66}, Zn^{67}, and Zn^{68} the recent xenon measurements of Johnson[10] have also been used. Though most of the differences between the two sets lie outside the errors, their apparent randomness suggests no constant systematic error between them.

Also in Table IV is shown a comparison between the two sets of results for the abundant iron isotopes. McMaster results obtained earlier have been recalculated using the present secondary standard masses and the two sets seem to be consistent.

TABLE III. Comparison of the mass excess $(M-A)$ obtained in the present investigation with the values obtained previously at this laboratory.

Isotope	Measured mass excess $(M-A)$ in mMU Present	Previous[a]	Δ[b]
Fe^{54}	−43.242±5	−43.07±5	0.17±5
Fe^{56}	−47.278±4	−47.40±10	−0.12±10
Fe^{57}	−46.491±7	−46.53±9	−0.04±9
Fe^{58}	−48.269±4	−48.09±40	0.18±40
Co^{59}	−48.081±3	Not measured	
Ni^{58}	−46.233±7	−46.67±9	−0.44±9
Ni^{60}	−50.177±6	−51.12±29	−0.94±29
Ni^{61}	−49.540±5	−51.06±23	−1.52±23
Ni^{62}	−51.967±7	−53.32±8	−1.35±8
Ni^{64}	−51.661±5[c]	−52.45±7	−0.79±7
Cu^{63}	−50.393±8	−50.87±5	−0.48±5
Cu^{65}	−51.573±5	−51.79±5	−0.22±5
Zn^{64}	−50.528±3	−50.46±2	0.07±2
Zn^{66}	−52.987±7	−52.92±5	0.07±5
Zn^{67}	−51.582±7	−51.99±5	−0.41±5
Zn^{68}	−53.544±5	−53.27±6	0.27±6
Zn^{70}	−52.428±6	−52.35±5	0.08±5

[a] See reference 9.
[b] Δ = present minus previous mass excess.
[c] This mass is believed to be in error. The corrected mass excess value is −51.715±4. See text for discussion.

[10] W. H. Johnson, Jr., Ph.D. thesis, University of Minnesota, 1956 (unpublished).

NUCLEAR ENERGY DATA

One may gain information concerning the correctness of the mass spectrometric data by comparing measured stable isotope mass differences with the mass differences calculated from the results of nuclear disintegration energy measurements. The relatively high precision of many of the β-decay energy and nuclear Q-value measurements renders this a sensitive test of the correctness of both sets of data.

A preliminary comparison between the two sets of data showed good agreement except for several isolated, large discrepancies. This led to an examination of the assignments made for the γ rays observed in neutron capture experiments and suggested changes in the Q values for some of the (n,γ) reactions in this region. This examination will first be discussed in detail and then an over-all comparison between the mass spectroscopic and nuclear data will be made.

In converting from energy units to mass units the revised conversion factor, 931.141±10 Mev/amu,[11] has been used. The neutron mass needed in converting some reaction Q values to mass differences was calculated using Wapstra's value for the $n-H^1$ mass difference, namely $n-H^1=783.0\pm0.7$ kev.[7] All errors have been combined by taking the square roots of the sums of the squares.

NEUTRON CAPTURE γ-RAY ASSIGNMENTS

The neutron capture γ-ray energy spectrum for the elements in this region has been investigated by Kinsey and Bartholomew[12] (Z even) and by Bartholomew and Kinsey[13] (Z odd). At the time of their work (1953) sufficient auxiliary data to enable them to identify positively the isotopic source of all observed γ rays did not exist. We examine the neutron capture γ-ray assignments by using measured atomic masses to predict the energy of the ground state transition and then compare the predictions with observed γ-ray energies. The results of this comparison are summarized in Table V. Transitions to excited states have been included whenever they help to clarify the assignments or when they are useful in inferring information concerning the correctness of the mass data. In cases where an unstable mass is needed in the γ-ray energy prediction, β-decay energy data are used to relate the unstable mass to a stable neighbor. The following discussion covers Table V element by element.

TABLE IV. Comparison of the present results with those obtained recently by the group at McMaster University.

Mass doublet or mass	Mass difference or mass Minnesota	McMaster	Δ[a] in mMU
	Values in mMU		
$C_2H_4O_2-Ni^{60}$	90.387 ±6	90.82±15[b]	0.43±15
$O_2-\frac{1}{2}Zn^{64}$	25.2633±26	25.45±15[c]	0.19±15
	Values in amu		
Fe^{54}	53.956 758±5	53.956 61±22[d]	−0.15±22
Fe^{56}	55.952 722±4	55.952 82±15[d]	0.10±15
Ni^{58}	57.953 767±7	57.953 80±15[b]	0.03±15
Ni^{60}	59.949 823±6	59.949 39±15[b]	−0.43±15
Zn^{64}	63.949 472±3	63.949 09±15[e]	−0.38±15
Zn^{66}	65.947 013±7	65.947 44±15[e]	0.43±15
Zn^{67}	66.948 418±7	66.948 74±20[e]	0.32±15
Zn^{68}	67.946 456±5	67.947 51±20[e]	1.05±20

[a] Δ = McMaster minus Minnesota results.
[b] See reference 6.
[c] See reference 5.
[d] Recalculation of previous McMaster results using the current secondary standard masses, H. E. Duckworth (private communication, 1956).
[e] Recalculated from reference 5 using Johnson's xenon masses; Xe^{132} =131.946 10±5, Xe^{134}=133.947 99±5, Xe^{136}=135.950 42±3 amu, reference 10.

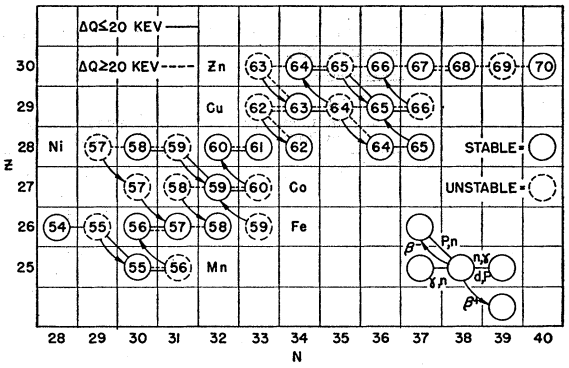

FIG. 1. Schematic representation of the nuclear reaction and β-decay paths connecting the isotopes under investigation. All paths shown were used in the mass difference comparison.

Iron

The transitions listed as ground state appear to have been correctly assigned previously. The deviation Δ_{Ex} for Fe^{55} seems to indicate an error either in the measured mass of Fe^{54} or in the $Fe^{55}-Mn^{55}-Mn^{56}-Fe^{56}$ reaction chain used to predict the mass of Fe^{55} (see Fig. 1). Another possibility is that a 65-kev excited state exists in Fe^{55} and all transitions observed here go to that level. However no other evidence indicates the existence of such a state.[14]

The discrepancy in the case of γ-ray A assigned to Fe^{58} may not be a mass error. The γ-ray coincidence spectrum given in the original paper shows peak A as being quite broad. It seems possible that energy A could be slightly lower, thus improving the agreement with the mass data.

Wapstra[7] assigned γ-ray G to the ground state transition in Fe^{59}. Our data suggest that this is not a ground state transition but rather one to an excited state, assuming that the Fe^{59} β-decay energy measurement is correct.

[11] Cohen, DuMond, Layton, and Rollett, Revs. Modern Phys. **27**, 363 (1955).
[12] B. B. Kinsey and G. A. Bartholomew, Phys. Rev. **89**, 375 (1953).
[13] G. A. Bartholomew and B. B. Kinsey, Phys. Rev. **89**, 386 (1953).
[14] For a review of excited state energies see Way, King, McGinnis, and van Lieshout, U. S. Atomic Energy Commission Report TID-5300, 1955 (unpublished).

TABLE V. Comparison between the observed neutron capture γ-ray energies and the ground state γ-ray transition energy calculated from the measured atomic masses. Some transitions to excited states are compared with the known excited state energies to help judge the correctness of the mass data.

Mass difference used[a]	Calculated maximum energy in Mev	Observed γ-ray energy in Mev[b]	Δ[c] in kev	Observed excited states in kev[d]	Δ_{Ex}[e] in kev
$Fe^{55}-Fe^{54}$	9.360±30	*B* 9.298±7	60±30	ground	60±30
		C 8.872±10	490±30	425±10	65±30
		D 8.345±11	1010±30	940±50	70±60
$Fe^{57}-Fe^{56}$	7.634±8	*E* 7.639±4	−5±9	ground	−5±9
		F 7.285±9	349±12	355±5	−6±13
		H 6.015±7	1619±11	1650±60	−31±60
		I 5.914±10	1720±13	(1719)[f]	
$Fe^{58}-Fe^{57}$	10.022±8	*A* 10.160±40	−138±40	ground	−138±40
		B 9.298±7	722±11	805±12	−83±17
		B' 9.20 ±20[g]	820±20		15±20
$Fe^{59}-Fe^{58}$	6.631±7	*G* 6.369±9	262±11	?	
$Co^{60}-Co^{59}$	7.498±7	*A* 7.486±6	12±9	ground	12±9
		B 7.201±6	297±9	289±3	6±9
		E 6.867±6	631±9	650±30[h]	−19±30
		F 6.690±6	808±9	820±30	−12±30
		J 5.966±6	1532±9	1480±30	52±30
		L 5.646±6	1852±9	1820±30	32±30
$Ni^{59}-Ni^{58}$	9.016±8	*A* 8.997±5	19±9	ground	19±9
		B 8.532±8	484±11	450±30[i]	31±30
		C 8.119±10	897±13	878±15[i]	16±20
		D 7.817±8	1199±11	1180±13[i]	16±17
$Ni^{61}-Ni^{60}$	7.773±8	*D* 7.817±8	−44±11	ground?	
$Ni^{62}-Ni^{61}$	10.626±9	No γ ray found with energy above 9.0 Mev			
$Ni^{63}-Ni^{62}$	6.825±10	*H* 6.839±10	−14±14	ground	
$Ni^{65}-Ni^{64}$	6.130±20[j]	*K* 6.100±20	30±30	ground?	
$Cu^{64}-Cu^{63}$	7.919±9	*A* 7.914±6	5±11	ground	5±11
		B 7.634±6	285±11	280±5	5±12
		C 7.296±9	623±13	510±50	110±50
		C' 7.160±20	759±20	840±50	−81±50
		E 6.690±30	1229±30	1290±50	61±60
$Cu^{66}-Cu^{65}$	7.057±20	*D* 7.010±20	47±30	ground	
$Zn^{65}-Zn^{64}$	7.992±6	*E* 7.876±7	116±9	114±4[k]	2±7
$Zn^{67}-Zn^{66}$	7.058±10	*G* 6.940±20	118±20	92±20	26±20
		G' 6.650±30	408±30	388±3	20±30
$Zn^{68}-Zn^{67}$	10.193±9	*A* 9.510±30	683±30	?	
		B 9.120±10	1073±14	1100±20	−27±25
$Zn^{69}-Zn^{68}$	6.50 ±20	*H* 6.490±20	100±200	ground	

[a] When the heavier nucleus is unstable, its mass is calculated from its stable neighbor by using β-decay energy data.
[b] Obtained from reference 12 (even Z), or from reference 13 (odd Z).
[c] Δ = maximum energy minus observed γ-ray energy.
[d] Excited state data is summarized in reference 14.
[e] $\Delta_{Ex} = \Delta$ minus the observed excited state energy.
[f] This state inferred from intensity considerations. See reference 12.
[g] This energy estimated from Fig. 6, reference 12.
[h] Error values are estimated from the data presented in reference 14.
[i] States taken from reference 15.
[j] Based upon the corrected Ni^{64} mass. See text.
[k] Excited state from reference 17.

Cobalt

The only question here is whether or not γ-ray *A* represents the ground state transition in Co^{60} since an excited state is known to exist at 58.9±0.9 kev.[14] The data here strongly suggest that the ground state assignment is correct. The randomness of the Δ_{Ex} values indicates no systematic error in either the energy or the mass measurements.

Nickel

Since the nickel masses previously obtained at this laboratory were incorrect by a rather large amount, some of the previous γ-ray assignments in nickel have now been modified. The present masses place new limits upon the maximum γ-ray energy that may be associated with capture in a given isotope. These energy limits show that γ-rays *B* and *C*, originally assigned to Ni^{61}, must now be assigned to Ni^{59}.

The assignment of γ-ray *D* is inconclusive, since it fits both the 1180-kev excited state of Ni^{59}, and the Ni^{61} ground state transition. These two energies appear to be slightly different, however, and the measured γ-ray energy may be the average of two unresolved components. This observation seems to be substantiated by the data obtained in the $Ni(d,p)$ reaction study of Pratt.[15] Tentatively we assign the measured energy of *D* to the $Ni^{60}(n,\gamma)Ni^{61}$ *Q* value.

[15] W. W. Pratt, Phys. Rev. **95**, 1517 (1954).

Assignment of γ-ray K to Ni^{65} must be considered tentative only. Because of its relatively low isotopic abundance, Ni^{65} gives a contribution to the γ-ray spectrum that is easily obscured by excited state γ rays from other isotopes. In making this prediction we have used the corrected Ni^{64} mass. This correction is discussed in the section covering the $A=64$ region.

Copper

The γ-ray assignments to the copper isotopes are clarified by the present work. From the mass determined energy limits, it is seen that γ-rays A to C' must come from Cu^{64}. Previously it was suggested that γ-ray B might come from Cu^{66}, but that now seems unlikely, unless the Cu^{66} β-decay energy is in error by a large amount ($\sim$600 kev). Also γ-ray B seems to match the 280-kev excited state in Cu^{65} seen in the investigation of low-energy capture γ rays.[16] Assignment of γ-ray E is open to question since it energetically could come from either isotope. The excited state agreement is better at Cu^{64}, as shown.

Zinc

Several assignment changes are made for this element. The $Zn^{64}(n,\gamma)Zn^{65}$ reaction is assigned a Q value of 7.990 ± 8 Mev because of the good agreement between the predicted maximum energy and the sum of the energies of γ-ray G and the 114 ± 4 kev excited state.[17] The assignments of γ-rays G and H to Zn^{67} and Zn^{69}, respectively, are new, being based entirely upon the mass data. The agreement of γ-ray G' with the excited state in Zn^{67} lends support to the correctness of the Zn^{67} ground state assignment. The $Zn^{66}(n,\gamma)Zn^{67}$ Q-value is obtained from the sum of the energy G and the 92-kev excited state, giving a value of 7.03 ± 0.02 Mev. Energetically, γ-rays A and B must come from Zn^{68}. Wapstra suggested,[7] and the data here confirms, the assignment of γ-ray B to the 1100-kev state,[14] giving a ground state Q value of 10.22 ± 0.02 Mev in good agreement with the mass prediction. Insufficient data exist with which to infer the energies of γ rays emitted with capture in the rare isotope, Zn^{70}.

MASS DIFFERENCE COMPARISON

A convenient method for comparing the measured masses with all the nuclear energy data is the calculation of mass differences of adjacent stable isotopes. Such mass differences have been calculated for all neighboring pairs of stable isotopes in this region along all possible paths as shown in Fig. 1, using all available nuclear energy data. Nuclear reaction Q values were taken from the review article of Van Patter and Whaling,[18] except for the new or revised Q values listed in Table VI. The (n,γ) Q values are derived from the examination of the neutron capture γ rays, as has been discussed. β-disintegration energies were taken primarily from the review article of King.[19]

TABLE VI. New or revised nuclear reaction Q values used in the comparison between the nuclear energy data and the measured atomic masses.

Reaction	Q-value in Mev	Reference
$Co^{59}(d,p)Co^{60}$	5.283 ± 3	a
$Ni^{60}(n,\gamma)Ni^{61}$	7.817 ± 8	b
$Ni^{62}(n,\gamma)Ni^{63}$	6.839 ± 10	c
$Ni^{64}(n,\gamma)Ni^{65}$	6.130 ± 20	b
$Cu^{63}(\gamma,n)Cu^{62}$	-10.800 ± 50	d
$Cu^{63}(d,p)Cu^{64}$	$5.66\ \pm4$	e
$Cu^{63}(p,n)Zn^{63}$	-4.149 ± 4	f
$Cu^{65}(\gamma,n)Cu^{64}$	-9.910 ± 110	d
$Cu^{65}(p,n)Zn^{65}$	-2.136 ± 3	f
$Cu^{65}(n,\gamma)Cu^{66}$	7.010 ± 20	b
$Zn^{64}(n,\gamma)Zn^{65}$	7.990 ± 8	b
$Zn^{66}(n,\gamma)Zn^{67}$	7.030 ± 20	b
$Zn^{67}(n,\gamma)Zn^{68}$	10.220 ± 20	b
$Zn^{68}(n,\gamma)Zn^{69}$	6.490 ± 20	b
$Zn^{68}(p,n)Ga^{68}$	-3.694 ± 6	e

[a] G. M. Foglesong and D. G. Foxwell, Phys. Rev. **96**, 1001 (1954).
[b] See text for discussion of γ-ray reassignments.
[c] See Table V.
[d] Bendel, McElhinney, and Tobin, Bull. Am. Phys. Soc. Ser. II, **1**, 192 (1956).
[e] D. C. Hoesterey, Phys. Rev. **87**, 216(A) (1952), and private communication. See reference 14.
[f] Obtained from an average of the values of Kington, Bair, Cohn, and Willard, Phys. Rev. **99**, 1393 (1955) and Brugger, Bonner, and Marion, Phys. Rev. **100**, 84 (1955).

In Table VII these calculated mass differences are compared with the spectrometrically determined results. The comparison column (Δ=measured minus calculated mass difference) shows a pattern of reasonably good agreement. In the following, two discrepancies are discussed. Discrepancies not mentioned are covered in the section on neutron capture γ-ray assignments.

Co^{57}

Wapstra[7] discussed the discrepancy in the nuclear cycles involving the Co^{57} β-decay energy and concluded that this energy was in error. Subsequently this decay energy value was revised[14] (see Table IX) and the over-all agreement in the cycles is now reasonably good, as the comparisons along alternate paths found in Table VII, lines 3–6 show.

$A=64$

Consideration of the region centered on Cu^{64} leads to the suggestion of a possible error in the measured mass of Ni^{64} (Table VII, lines 11, 12, and 14). Considerable difficulty was experienced in obtaining a Zn^{64}-free Ni^{64} ion current. Since these two differ in mass by only 1 in 60 000, and because of their unfavorable relative abundance ratio, it seems possible that a contamination could have been present and remained undetected. The spectrometer resolution was only 1 in 30 000 for these runs and the Ni^{64} peak was of very low intensity.

[16] T. H. Braid, Phys. Rev. **102**, 1109 (1956).
[17] B. Crasemann, Phys. Rev. **93**, 1034 (1954); J. B. Marion and R. A. Chapman, Phys. Rev. **101**, 283 (1956).
[18] D. Van Patter and W. Whaling, Revs. Modern Phys. **26**, 402 (1954).
[19] R. W. King, Revs. Modern Phys. **26**, 327 (1954).

TABLE VII. Comparison of measured stable isotope mass excess differences with those calculated from nuclear reaction Q values and β-disintegration energies.

Mass difference	Path[a]	Mass excess difference in μMU Measured	Calculated[b]	Δ[c] in μMU
(1) $Fe^{56}-Fe^{54}-2$	Fe^{55}, Mn^{55}, Mn^{56}	-4036 ± 6	-3976 ± 30	-60 ± 30
(2) $Fe^{57}-Fe^{56}-1$	direct	787 ± 8	781 ± 4	6 ± 9
(3) $Fe^{58}-Fe^{57}-1$	direct	-1778 ± 8	-1926 ± 40	148 ± 40
	Co^{59}, Ni^{58}		-1630 ± 350	-150 ± 350
(4) $Co^{59}-Fe^{58}-1$	Co^{58}	188 ± 5	446 ± 200	-258 ± 200
	Ni^{58}, Fe^{57}		740 ± 300	-550 ± 300
(5) $Ni^{58}-Fe^{57}-1$	Ni^{57}, Co^{57}	258 ± 10	650 ± 300	-390 ± 300
	Co^{59}, Fe^{58}		360 ± 200	-100 ± 200
(6) $Co^{59}-Ni^{58}-1$	Ni^{59}	-1848 ± 7	-1836 ± 6	-12 ± 9
	Fe^{58}, Fe^{57}		-2120 ± 350	270 ± 350
(7) $Ni^{60}-Co^{59}-1$	Co^{60}	-2096 ± 7	-2097 ± 12	1 ± 14
(8) $Ni^{61}-Ni^{60}-1$	direct	637 ± 8	587 ± 8	50 ± 11
(9) $Cu^{63}-Ni^{62}-1$	Cu^{62}	1574 ± 11	1610 ± 60	-36 ± 60
(10) $Zn^{64}-Cu^{63}-1$	Cu^{64}	-135 ± 9	-129 ± 6	-6 ± 11
	Zn^{63}		-2 ± 160	-137 ± 160
(11) $Ni^{64}-Cu^{63}-1$	Cu^{64}	-1268 ± 9	-1316 ± 6	48 ± 11
(12) $Zn^{64}-Ni^{64}$	Cu^{64}	1133 ± 6	1187 ± 3	-54 ± 7
	$Zn^{65}-Ni^{65}$		1217 ± 30	-84 ± 30
(13) $Cu^{65}-Cu^{63}-2$	Cu^{64}	-1180 ± 9	-1180 ± 110	0 ± 110
	$Zn^{65}-Zn^{63}$		-1043 ± 170	-137 ± 170
(14) $Cu^{65}-Ni^{64}-1$	Cu^{64}	88 ± 7	144 ± 110	-56 ± 110
	Ni^{65}		174 ± 30	-86 ± 30
(15) $Cu^{65}-Zn^{64}-1$	Cu^{64}	-1045 ± 6	-1045 ± 110	0 ± 110
	Zn^{65}		-1043 ± 8	2 ± 10
(16) $Zn^{66}-Cu^{65}-1$	Cu^{66}	-1414 ± 9	-1360 ± 30	-54 ± 30
	Zn^{65}		-1540 ± 200	126 ± 200
(17) $Zn^{66}-Zn^{64}-2$	Zn^{65}	-2459 ± 8	-2590 ± 200	130 ± 200
	$Cu^{66}-Cu^{64}$		-2405 ± 110	-55 ± 110
(18) $Zn^{67}-Zn^{66}-1$	direct	1405 ± 10	1435 ± 20	30 ± 20
(19) $Zn^{68}-Zn^{67}-1$	direct	-1962 ± 9	-1991 ± 20	28 ± 22
(20) $Zn^{70}-Zn^{68}-2$	Zn^{69}	1116 ± 8	1120 ± 200	-4 ± 200

[a] Paths refer to energy connections shown in Fig. 1.
[b] See text for method of calculation.
[c] Δ = measured minus calculated mass difference.

In view of this possible contaminant we examined the effect of a correction in the Ni^{64} mass which improves the agreement between the measured and calculated $Zn^{64}-Ni^{64}$ mass differences. If we assume the mass of Zn^{64} and the $Zn^{64}-Ni^{64}$ mass difference as calculated from the Cu^{64} β-decay energies to be correct, the Ni^{64} mass is lowered by 54 μMU. The effect of such a change is shown in Table VIII where the appropriate lines from Table VII are reproduced, the only difference being the use of the lowered Ni^{64} mass in determining the measured mass differences. The agreement along all paths improves greatly and also reinforces the belief that the γ ray previously assigned to neutron capture in Ni^{64} is correct.

TABLE VIII. The effect of lowering the Ni^{64} mass by 54 μMU on the mass differences shown in Table VII.[a]

Isotope difference	Path	Mass excess difference in μMU Measured	Calculated	Δ[b] in μMU
(11) $Ni^{64}-Cu^{63}-1$	Cu^{64}	-1322 ± 9	-1316 ± 6	-6 ± 11
(12) $Zn^{64}-Ni^{64}$	Cu^{64}	1187 ± 3	1187 ± 3	standard
	$Ni^{65}-Zn^{65}$		1217 ± 30	-30 ± 30
(14) $Cu^{65}-Ni^{64}-1$	Cu^{64}	142 ± 7	144 ± 110	-2 ± 110
	Ni^{65}		174 ± 30	-32 ± 30

[a] The new Ni^{64} mass is $63.948\,285\pm4$ amu.
[b] Δ = measured minus calculated mass difference.

UNSTABLE ISOTOPE ATOMIC MASSES

With the measured stable isotope atomic masses as a base, it is possible to use the Q value and β-decay energies to calculate the masses of the unstable isotopes in this region. In doing this the β-disintegration energies summarized by King[19] have been supplemented by the more recent results shown in Table IX. The resulting unstable masses are shown as mass excesses in Table X together with an indication of the path of calculation. Where it is possible to base the unstable mass on more than one stable isotope this has been done, and the final result shown is the average of the separate mass excesses. If the individual results for a given mass are consistent, a weighted average is used. Inconsistent results are averaged with equal weight, except that results with errors greater than 100 kev are eliminated.

NUCLEON BINDING ENERGIES

Binding energies of nucleons in a nucleus may be investigated in an over-all way by studying the easily calculated average binding energy per nucleon. Specifically, this is

$$\text{T.B.E.}/A=[Z(M_p+M_e)+N(M_n)-{}_zM^A]/A, \quad (1)$$

where T.B.E. = the total binding energy (nuclear and electronic) and ${}_zM^A$ is the mass of the atom whose

nucleus is under consideration. M_p, M_e, and M_n are the masses of the proton, electron, and neutron, respectively. For our work here (M_p+M_e) may be replaced by M_H, the mass of the hydrogen atom, without introducing significant error.

This average binding energy has been calculated for all the stable isotopes whose masses were measured in this investigation and the results are summarized in Table XI. Errors associated with these values are due primarily to the error in the $n-H$ mass difference. In Fig. 2 these results are shown graphically with T.B.E./A plotted as a function of N. The curves drawn through the points have no mathematical significance but are for ease of interpretation. Collins *et al.*[20] proposed making a least squares fit of the mass data to a parabola, primarily because of the parabolic shape assumed for isobaric sections of the binding energy surface. Because of the increased experimental accuracy of the present measurements, such fitting is inconclusive. Various trials were made, and the agreement with parabolic shape was always no closer than about five times the quoted errors. Furthermore, it was found to be possible to materially alter the shape of the parabola, but not the quality of fit, by eliminating the data points one by one and recalculating the curve. For these and other reasons it seems reasonable to assume that the parabolic shape is indeed a measure of the gross variation of the binding energy surface, but that other effects modify the curve sufficiently so that it cannot be used as a check upon the consistency of the present, more precise data.

It is interesting to note that T.B.E./A reaches a maximum at nickel, $Z=28$, and falls steadily for higher Z. This is one effect that may perhaps be associated with the closing of the proton shell at the "magic number" $Z=28$.

Information of a more specific nature is obtained by calculating the binding energy of the last nucleon (neutron or proton) added to the nucleus. This binding energy is just that mass which disappears when a nucleon is added to a nucleus of mass $A-1$ to form a nucleus of mass A. It is readily calculated from atomic mass values.

[20] Collins, Johnson, and Nier, Phys. Rev. **94**, 398 (1954).

TABLE IX. New β-disintegration energies used in the calculation of unstable isotope atomic masses.

Isotope	Decay energy in kev	Reference
Co^{55}	3457±13	a
Cu^{60}	6270±30	b
Co^{57}	700±200	c
Co^{61}	1490±20	c
Co^{62}	5000±300	d
Zn^{62}	1697±10	d

[a] R. S. Caird and A. C. G. Mitchell, Phys. Rev. **94**, 412 (1954); **93** 916(A) (1954).
[b] R. H. Nussbaum *et al.*, Physica **20**, 555 (1954).
[c] See reference 14.
[d] R. H. Nussbaum *et al.*, Physica **20**, 571 (1954).

TABLE X. Unstable isotope atomic mass excesses $(M-A)$.

Unstable isotope	Calculated from	Mass excess in mMU	Final mass excess in mMU
Mn^{56}	Fe^{56}		−43.358±30
Fe^{53}	Fe^{54}		−37.407±200
Fe^{55}	Fe^{54}	−44.243±9	
	Fe^{56}	−44.309±30	−44.279±30
Fe^{59}	Co^{59}		−46.405±7
Co^{55}	(Fe^{55})[a]		−40.566±35
Co^{56}	Fe^{56}		−42.306±20
Co^{57}	(Ni^{57})[b]	−46.133±200	
	Fe^{57}	−45.741±200	−45.937±140
Co^{58}	Co^{59}	−46.061±200	
	Fe^{58}	−45.800±11	−45.800±11
Co^{60}	Co^{59}	−47.149±12	
	Ni^{60}	−47.148±7	−47.148±6
Co^{61}	Ni^{61}		−47.940±20
Co^{62}	Ni^{62}		−46.567±30
Ni^{57}	Ni^{58}	−42.653±200	
	(Co^{57})[c]	−42.457±300	−42.593±200
Ni^{59}	Ni^{58}	−46.913±9	
	Co^{59}	−46.931±30	−46.915±9
Ni^{63}	Cu^{63}		−50.312±8
Ni^{65}	Cu^{65}	−49.313±20	
	Ni^{64}	−49.281±20	−49.297±14
Cu^{60}	Ni^{60}		−43.443±30
Cu^{61}	Ni^{61}		−47.146±8
Cu^{62}	Ni^{62}	−47.747±20	
	Cu^{63}	−47.779±50	−47.751±18
Cu^{64}	Cu^{63}	−49.907±10	
	Cu^{65}	−49.913±110	
	Zn^{64}	−49.913±4	
	Ni^{64}	(−49.913±4)[d]	−49.912±4
Cu^{66}	Cu^{65}	−50.113±20	
	Zn^{66}	−50.167±20	−50.140±30
Cu^{67}	Zn^{67}		−50.968±11
Zn^{62}	(Cu^{62})[e]		−45.929±20
Zn^{63}	Cu^{63}	−46.791±9	
	Zn^{64}	−46.928±170	−46.791±9
Zn^{65}	Zn^{64}	−50.126±8	
	Zn^{66}	−49.997±200	
	Cu^{65}	−50.126±6	−50.126±5
Zn^{69}	Zn^{68}	−51.529±20	
	Zn^{70}	−51.538±200	−51.529±20

[a] Based upon Fe^{54} and Fe^{56} through the average Fe^{55} mass.
[b] Based on Ni^{58} through Ni^{57}.
[c] Based on Fe^{57} through Co^{57}.
[d] The corrected Ni^{64} mass is based upon this value. It is not used in obtaining the final Cu^{64} mass.
[e] Based upon Ni^{62} and Cu^{63} through the average Cu^{62} mass.

Neutron Interactions

Wherever sufficient data exist, the binding energy of the last neutron B_n has been calculated. The results

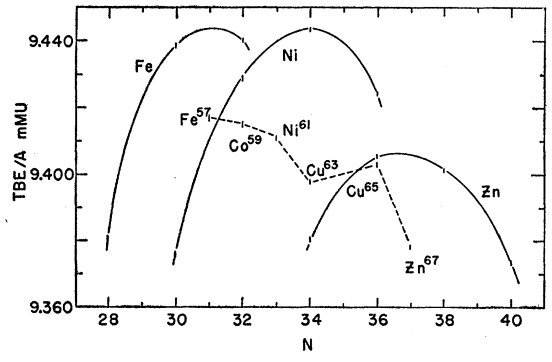

FIG. 2. Average total binding energy per nucleon. Data are taken from Table XI.

TABLE XI. Average binding energy per nucleon for the stable isotopes of the elements studied in this investigation (in mMU).

Stable isotope	TBE/A[a]	Stable isotope	T.B.E./A[a]
Fe^{54}	9.3810	Cu^{63}	9.3979
Fe^{56}	9.4389	Cu^{65}	9.4033
Fe^{57}	9.4172		
Fe^{58}	9.4405	Zn^{64}	9.3804
		Zn^{66}	9.4057
Co^{59}	9.4152	Zn^{67}	9.3785
		Zn^{68}	9.4015
Ni^{58}	9.3763	Zn^{70}	9.3737
Ni^{60}	9.4290		
Ni^{61}	9.4112		
Ni^{62}	9.4435		
Ni^{64}	9.4253		

[a] All values have an associated error of ± 0.5 μMU due primarily to the error in the $n-H$ mass difference. T.B.E./A =average binding energy per nucleon.

are listed in Table XII. Variations in B_n with respect to neutron number N of the final nucleus are shown graphically in Fig. 3. From this figure several observations may be made.

Consider first a neutron added to form a nucleus of odd N. This nucleon must enter an empty two-particle energy level and neutrons in this category have a binding energy range of 7 to 10 mMU here, the energy decreasing with higher N in each element. Decreasing odd neutron binding in a given element is expected because of the saturation of n-p forces. Conversely, a given neutron (N constant) is generally more strongly bound as Z increases because of the increased number of n-p interactions. This effect is consistent with the concept of nuclear symmetry, that is, except for the modifying influence of the Coulomb repulsion, nuclei with N and Z approximately equal tend to be most stable.

When one considers the neutron added to form a nucleus of even N, it is seen to be bound more strongly than its predecessor. Even neutron binding-energy values range from 10 to 13 mMU in this region, with the same sort of N and Z variations as discussed for

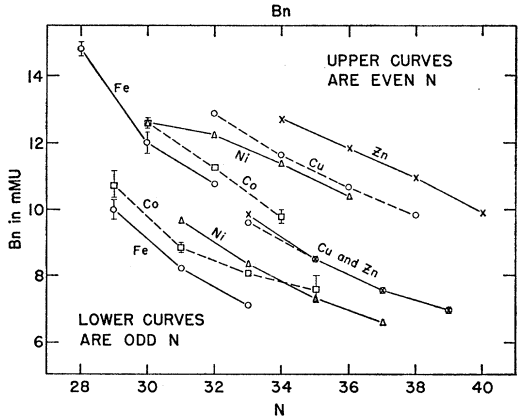

FIG. 3. Binding energy B_n of the last neutron in the nucleus. Data are taken from Table XII.

the odd N last neutrons. The even neutron occupies the same two-particle energy level as the preceding odd one and its additional binding energy is attributed to "pairing energy." Neutron pairing energy P_n is taken as the difference between the B_n values for the last and next to last neutrons in even N nuclei. Values of P_n for all possible neutron pairs are summarized in

TABLE XII. Total binding energy of the last proton and the last neutron for all nuclei where sufficient data enables their calculation. Values in mMU.

Isotope	N	B_n[a]	B_p[b]
Fe^{54}	28	14.82 ±20	
Fe^{55}	29	10.022±30	
Fe^{56}	30	11.984±30	11.392±12[c]
Fe^{57}	31	8.198±8	11.277±30
Fe^{58}	32	10.763±8	
Fe^{59}	33	7.212±8	
Co^{55}	28		5.468±35
Co^{56}	29	10.725±40	6.171±40
Co^{57}	30	12.62 ±14	6.80 ±14
Co^{58}	31	8.85 ±14	7.453±13
Co^{59}	32	11.266±11	7.956±5
Co^{60}	33	8.052±7	8.887±8
Co^{61}	34	9.777±20	
Co^{62}	35	7.612±40	
Ni^{57}	29		8.43 ±20
Ni^{58}	30	12.63 ±20	8.44 ±14
Ni^{59}	31	9.667±11	9.26 ±20
Ni^{60}	32	12.247±11	10.242±7
Ni^{61}	33	8.348±8	10.536±8
Ni^{62}	34	11.412±9	12.171±20
Ni^{63}	35	7.330±11	11.889±30
Ni^{64}	36	10.388±9	
Ni^{65}	37	6.567±14	
Cu^{60}	31		4.67 ±20
Cu^{61}	32	12.688±30	5.113±10
Cu^{62}	33	9.590±20	6.355±19
Cu^{63}	34	11.627±20	6.570±13
Cu^{64}	35	8.504±9	7.744±9
Cu^{65}	36	10.646±6	7.966±6
Cu^{66}	37	7.552±30	8.987±30
Cu^{67}	38	9.813±30	
Zn^{62}	32		6.927±20
Zn^{63}	33	9.847±20	7.183±20
Zn^{64}	34	12.722±9	8.279±9
Zn^{65}	35	8.536±6	8.358±6
Zn^{66}	36	11.846±9	9.558±8
Zn^{67}	37	7.580±10	9.586±30
Zn^{68}	38	10.947±9	10.720±12
Zn^{69}	39	6.970±20	
Zn^{70}	40	9.884±20	

[a] B_n =total binding energy of the last neutron in the listed nucleus.
[b] B_p =total binding energy of the last proton in the listed nucleus. Based upon the Mn^{55} mass doublet of reference 9.

Table XIII and are plotted with final neutron number as abscissa in Fig. 4.

Examination of these results shows several interesting features, the most obvious being a correlation between proton number Z and P_n for a given pair (N constant). In odd Z nuclei, here those of cobalt and copper, P_n is generally lower than in nuclei of even Z. Explanation of this difference seems to be connected with the fact that in odd Z nuclei the odd proton may interact more

strongly with the individual neutrons, reducing the pairing energy. In even Z nuclei all the protons are paired and hence interact less strongly with the neutrons. This reduction in pairing energy due to the presence of an unpaired nucleon of the other type is observed also for proton pairs in odd-N nuclei and is mentioned below.

Mayer and Jensen[21] discuss pairing energy and point to the correlation between it and the magnitude of the spin of the intermediate nucleus formed when only the first pair member is present. According to their arguments, calculations show that a pair of nucleons in an orbit of high total angular momentum interact to give a greater pairing energy than a pair of nucleons occupying a lower total angular momentum level.

In an attempt to correlate this effect with the data collected here, the angular momentum assignments for the levels occupied by the various neutron pairs have been included in Fig. 4. These assignments are predicted by using the nuclear shell model. Measured nuclear spins have been used as a guide wherever possible.

TABLE XIII. Pairing energy of the last pair of neutrons in the listed nuclei (in mMU).

Isotope	N	P_n[a]	Isotope	N	P_n[a]
Fe^{56}	30	1.96 ±6	Cu^{63}	34	2.04 ±4
Fe^{58}	32	2.565±15	Cu^{65}	36	2.142±12
			Cu^{67}	38	2.26 ±6
Co^{57}	30	1.89 ±16			
Co^{59}	32	2.42 ±14	Zn^{64}	34	2.875±30
Co^{61}	34	1.725±25	Zn^{66}	36	3.263±13
			Zn^{68}	38	3.367±16
Ni^{60}	32	2.580±20	Zn^{70}	40	2.914±40
Ni^{62}	34	3.064±14			
Ni^{64}	36	3.058±18			

[a] P_n = pairing energy of the last neutron pair in the listed nucleus.

Because the $p_{3/2}$ and $f_{5/2}$ levels are relatively close together in energy, and because the $f_{5/2}$ pairing energy may be greater than the $p_{3/2}$, it is difficult to predict the actual level configuration for $N=33$, 35, and 37. The possibility exists that the presence of unpaired protons perturbs the pairing energy in such a manner as to cause the level filling to vary with Z.

That the angular momentum of the level occupied by the pair does not totally explain the variations in P_n becomes apparent upon examination of the data. In the case of iron the two pairs have the same angular momentum, yet the second pair ($N=32$) has a P_n greater than that of the first pair. For zinc the final pair ($N=40$) occupies a $p_{1/2}$ level, yet its pairing energy is essentially the same as that for the first pair ($N=34$) in a $p_{3/2}$ or $f_{5/2}$ level. Some correlation between angular momentum and pairing energy is shown by the rise of P_n from the first to the second pair in nickel ($p_{3/2}$ to a possible $f_{5/2}$), and the decrease from the third pair ($N=38$) to the last pair in zinc ($f_{5/2}$ to $p_{1/2}$).

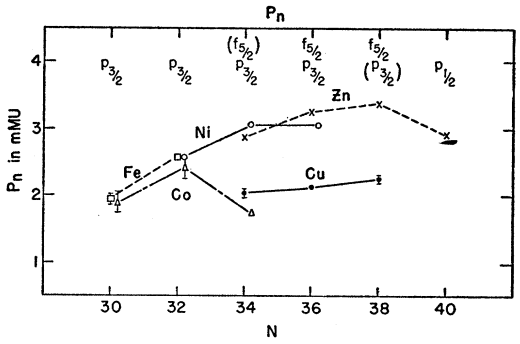

FIG. 4. Pairing energy P_n of the last neutron pair in the nucleus. Data are taken from Table XIII. Also shown is the angular momentum assignment for the level occupied by each neutron pair. These level assignments are derived from the nuclear shell model.

Considering specific neutron pairs, values of P_n seem to be relatively independent of Z, except for the odd or even character mentioned above. For example, at $N=34$, the pairing energy is essentially the same in nickel and zinc and also in copper and cobalt.

A reasonable explanation of the over-all situation may be as follows. Assume that the neutron level filling pattern is similar for these elements. Further assume that pairing energy is influenced by angular momentum and that the energy difference between odd and even Z depends primarily upon the presence or absence of an unpaired proton. Then variations in P_n may possibly be explained not only in terms of relative angular momentum but also in terms of interactions of the pair with other pairs that may be present. In the cases examined here, the second pair added to the nucleus is paired more strongly than the first, and the third pair shows a P_n generally equal to that of the second pair. This suggests the existence of such interactions between neutron pairs, but the relatively meager data presented make impossible more exact conclusions.

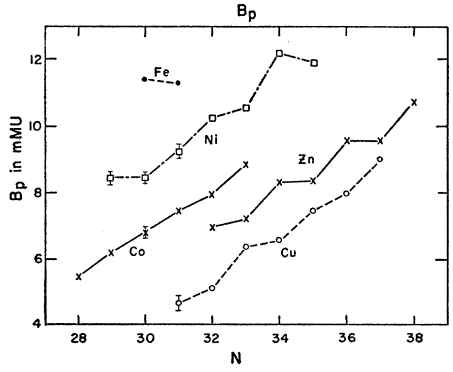

FIG. 5. Binding energy B_p of the last proton in the nucleus. Data are taken from Table XII.

[21] M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure* (John Wiley and Sons, Inc., New York, 1955).

TABLE XIV. Total pairing energy of the last pair of protons in the listed nickel and zinc nuclei (in mMU).

Nickel isotope	N	P_p[a]	Zinc isotope	N	P_p[a]
Ni^{57}	29	2.26 ±20	Zn^{62}	32	1.814±25
Ni^{58}	30	1.64 ±30	Zn^{63}	33	0.828±40
Ni^{59}	31	1.81 ±20	Zn^{64}	34	1.727±18
Ni^{60}	32	2.286±9	Zn^{65}	35	0.614±12
Ni^{61}	33	1.649±15	Zn^{66}	36	1.592±13
			Zn^{67}	37	0.59 ±6

[a] P_p = total pairing energy for the last proton pair in the listed nucleus Values are not corrected for Coulomb interaction. See text for discussion.

Proton Interactions

Specific information regarding proton interactions is obtained by calculating, in a manner analogous to the neutron case, the binding energy B_p of the last proton wherever sufficient data exists. Results of this computation are also shown in Table XII. Variations in B_p are shown in Fig. 5. Study of the figure reveals the same general features as did the neutron data.

In a given element, B_p increases with increasing N because of the larger possible number of n-p interactions. Also, for N constant, B_p decreases with increasing Z, although pairing energy obscures this result in the figure. The regularity of the curves for copper and zinc is not reflected into the cobalt and nickel data. No direct explanation of this is offered here. However, in nickel $Z=28$, a magic number, and one may expect nuclear effects to deviate from a regular pattern near magic numbers. The best test of these regularities would be to obtain data for elements with Z greater than that for zinc.

The effect of pairing energy for proton pairs can also be seen in Fig. 5. The last proton in nickel and zinc is more strongly bound than in cobalt and copper, respectively. Values of the proton pairing energy P_p have been calculated for all nickel and zinc nuclei where data exists and the results are presented in Table XIV. Pairing energy values are not corrected for the Coulomb interaction because the correction here is essentially constant and because the uncertainty in the method of its calculation introduces an unnecessary uncertainty in the values.

In Fig. 6 are shown the variations of P_p with respect to Z and N. The most significant effect shown is that mentioned above; namely that P_p is lower when an odd neutron is present in the nucleus. Considering the zinc data, P_p is considerably greater when N is even rather than odd. The nickel case is not as clear, although the first two points ($N=29$ and 30) are the only ones that deviate from the pattern. These two points have large associated errors and therefore great weight should not be given to them. Although the proton number 28 shows very little evidence of being magic (i.e. no large, abrupt changes are observed in nucleon binding energies as Z crosses 28), the irregularity in the nickel P_p values may be associated with this value of Z. Additional data both above and below this region might clarify the situation.

The data suggest that P_p is essentially neutron number independent, provided N is either always even or always odd. The odd-nuetron interaction with the proton pair is stronger than the odd-proton interaction with the neutron pair. It is interesting to note that while the nickel pair is presumably in an $f_{7/2}$ level and the zinc pair in a $p_{3/2}$ one, P_p for the two is essentially

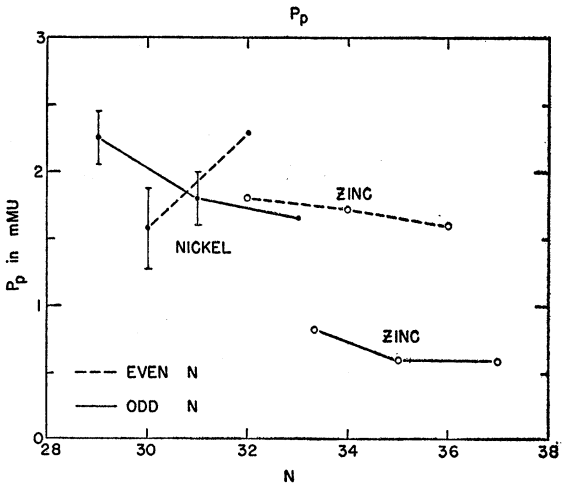

FIG. 6. Pairing energy P_p of the last proton pair in nickel and zinc nuclei. Data are taken from Table XIV.

the same. Apparently angular momentum effects are masked.

The data presented serve to emphasize the point that nucleon interactions in the nucleus are not to be interpreted in an elementary way and that much more data are needed to complete the picture.

ACKNOWLEDGMENTS

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