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Nuclear Shell Structure and Beta-Decay. II. Even *A* Nuclei

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A systematics of the β-transitions of even A nuclei is given. An interpretation of the character of the transitions in terms of nuclear shell structure is achieved on the hypothesis that the odd nucleon groups have the same structure as in odd A nuclei, together with a simple coupling rule between the neutron and proton groups in odd-odd nuclei.

A. THE COUPLING OF ODD PROTON AND NEUTRON GROUPS

IN the preceding paper[1] the β-decay properties of nuclei with odd mass number were discussed on the basis of our present knowledge of nuclear shell structure. In the present paper the discussion is extended to cover nuclei with even A. The general background, arguments, and references are the same as in I and need not be repeated here.

The situation is somewhat more complex than for odd A nuclei. A β-transition for an even A nucleus demands at one end point an even-even nucleus, which, in so far as we know, has zero spin. The other end point, mostly the initial nucleus, is of odd-odd type, in which there will be a coupling of neutron and proton groups, each of which will contribute to the resultant spin. Unfortunately only a very few spins of odd-odd nuclei have been measured so far; among these are several very high ones (Be^{10}, Na^{22}, K^{40}, Lu^{176}). The frequent occurrence of highly complex β-spectra with series γ-rays is also an indication that the spins of odd-odd nuclei are often quite large.

Of course, not much can be said *a priori* about the coupling between the proton and neutron groups. The persistence of the islands of isomerism (I, reference 1), leads to the suspicion that their configurations are largely independent of each other, and that their structure must in the main be preserved. More definite information can be obtained from the study of those β-transitions which connect the ground states of the initial and final nucleon.

The resultant pattern, which will be discussed in greater detail later, resembles closely the pattern of the odd A nuclei. Of particular interest are the groups of allowed transitions with neutron and proton numbers below 50 and of the first-forbidden transitions with $\Delta I=2$, which can be recognized by a value of $\log(W_0^2-1)$ ft of about 10 and by the shape of their spectra, if observed. These transitions can be interpreted in an entirely unforced manner by assuming that the respective odd proton and neutron groups have the same Schmidt orbitals as occur for the same nucleon numbers in odd A nuclei and that the spins of the neutron and proton groups are antiparallel, that is, couple to a minimum resultant. An inspection of the orbitals involved reveals further that they belong in these cases always to opposite Schmidt groups. Conversely, in light nuclei for which the expected orbitals for the neutron and proton groups are identical, the indications are always for a high resultant spin. We are thus led to the following hypotheses:[2]

(1) The individual configurations of neutrons and protons in odd-odd nuclei are the same as in odd A nuclei with the same number of nucleons in the odd particle group.

(2) If the odd neutron and proton groups belong to different Schmidt groups, then their resultant spins will subtract.

(3) If the odd neutron and proton groups belong to the same Schmidt group, their spins will couple to a larger than minimum resultant.

In terms of the notation for orbitals (2) and (3) can be expressed as follows: If the spins of the odd particle groups are $j_1=l_1\pm\frac{1}{2}$ and $j_2=l_2\mp\frac{1}{2}$, then the resultant spin is $I=|j_1-j_2|$. If $j_1=l_1\pm\frac{1}{2}$, $j_2=l_2\pm\frac{1}{2}$, then $I>|j_1-j_2|$.

The magnitude of the resultant spins in case (3) will be discussed later. In many, but not all, cases they seem to be near the possible maximum j_1+j_2.

The subsequent discussion is based on the above rules. They restrict greatly the choice of possible assignments, and the fact that it is possible to carry through the scheme on this basis gives strong support for its validity.

B. DISCUSSION

The complete material on even A nuclei is collected in Table II, Sec. C. Here we discuss as in I the transitions which go to the ground state ordered accordingly to type. They are given in Table I. It is to be noted that the nucleon numbers refer to the odd-odd nucleons involved in these transitions, and that the assignments

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[1] Mayer, Moszkowski, and Nordheim, Revs. Modern Phys. 23, 315 (1952), quoted henceforth as I.

[2] L. W. Nordheim, Phys. Rev. 78, 294 (1950).

refer to the neutron and proton configurations in this same nucleus. The even-even nuclei are assumed throughout to have spin zero and even parity.

The composition rules introduced in Sec. A exclude the occurrence of allowed transitions with spin change 0 and of first-forbidden transitions with spin change 1.

A very numerous group in the allowed class is formed by nuclei with $Z=45$ to 49 and N from 59 to 69. There is no analog to this group among the odd A nuclei. The only possibility to account for the absence of parity change in the shell scheme is with the help of the $g_{9/2}$ orbitals for $Z<50$. This demands the assignment of the orbital $g_{7/2}$ to the neutrons, which is not observed in this range in odd A nuclei. However the situation is here somewhat different. In odd A nuclei there is a definite discrimination against high spins for odd neutron numbers above 50. The assignment $g_{9/2}$–$g_{7/2}$ proposed for the group under discussion gives a total spin of only 1, so that a mechanism working against high spins may not be operative here, and a small coupling energy between the neutron and proton groups may produce a change in the preference of orbitals.

The presence of a first-forbidden group with $\Delta I=2$, of course, does not in itself prove rule (2) since a resultant spin 1 in place of 0 would not show up in the ft values. The latter fall within the same limits as given in I for odd A nuclei. Feenberg and Trigg[3] have remarked that, for even A, ft values for allowed transitions are somewhat lower and for first-forbidden transitions with $\Delta I=2$ somewhat higher than for odd A nuclei, and such a tendency is indeed reflected in the figures given here. The ft values for first-forbidden transitions with $\Delta I=2$ are, however, strictly comparable in the two cases.

The conclusion of I of the smallness of the matrix elements for second forbidden transitions is borne out by the high $\log ft$ values for Be^{10}, Na^{22}, and Cl^{36}, which lie all in the neighborhood of 14.

A special discussion is required for the cases where the orbital assignments lead to a change of the Schmidt angular momentum by 2 units, that is, no change in parity, while the spin change is 1. According to the formal selection rules such transitions should be allowed. In case the orbital angular momentum were a good quantum number, these transitions would be second forbidden. Among the cases for odd A nuclei (*I*, Table II) O^{19}, Si^{31}, and Ge^{69} show $\log ft$ values, respectively, of 5.5, 5.9, 6.0, which are somewhat high for allowed transitions but fall just within the limits of the group. Zn^{65} with $\log ft=7.4$ falls definitely out of line, while no first forbidden interpretation is compatible with the shell model. Pd^{109} with 6.2 is again a borderline case. The evidence from this transition is, however, not conclusive since it goes to the *meta*state of Ag^{109}, whose spin and parity are subject to doubt.

For even A there is the puzzling case of C^{14}, where the spin change is measured to be 1 while $\log ft=9$. The

TABLE I. Classification of β-decays to ground state of even A nuclei according to changes in spin (ΔI) and parity (no, yes). Column 1: Initial isotope Z-Element-A. Column 2: Sign of emitted charge, and maximum energy in Mev. Column 3: Initial and final nucleon number in this order. Column 4: Assignment of orbitals to the proton and neutron groups in the odd-odd nucleus. Column 5: Log ft. Column 6: $\mathrm{Log}(W_0^2-1)ft$ for $\Delta I=2$, yes. W_0 = energy of β-transition in units mc^2. Column 7: Observed spin of odd-odd nucleus.

1	2	3	4	5	6	7
(a) $\Delta I=1$. No (allowed)						
5 B 12	−13.4	5–7	$p_{3/2}-p_{1/2}$	4.2		
7 N 12	+16.6	7–5	$p_{1/2}-p_{3/2}$	4.1		
15 P 30	+ 3.5	15–15	$s_{1/2}-s_{1/2}$	5.0		
15 P 34	− 5.1	15–19	$d_{5/2}-d_{3/2}$	4.7		
31 Ga 70	− 1.65	31–39	$p_{3/2}-p_{1/2}$	5.0		
35 Br 78	+ 2.3	35–43	$p_{3/2}-p_{1/2}$	4.4+		
35 Br 80	+ 0.7	35–45	$p_{3/2}-p_{1/2}$	4.3+		
	− 2.0			5.4+		
44 Ru 106	− 0.039	45–61	$g_{9/2}-g_{7/2}$	4.3		
45 Rh 104	− 2.6	45–59	$g_{9/2}-g_{7/2}$	4.7+		
45 Rh 106	− 3.55	45–61	$g_{9/2}-g_{7/2}$	5.2		
46 Pd 112	− 0.2	47–65	$g_{9/2}-g_{7/2}$	4.0		
47 Ag 106	+ 2.04	47–59	$g_{9/2}-g_{7/2}$	4.7+		
47 Ag 108	− 2.8	47–61	$g_{9/2}-g_{7/2}$	5.3		
47 Ag 110	− 2.86	47–63	$g_{9/2}-g_{7/2}$	4.7+		
49 In 110	+ 1.6	49–61	$g_{9/2}-g_{7/2}$	4.7+		
49 In 114	− 1.98	49–65	$g_{9/2}-g_{7/2}$	4.4		
49 In 116	− 2.8	49–67	$g_{9/2}-g_{7/2}$	4.4		
49 In 118	− 1.5	49–69	$g_{9/2}-g_{7/2}$	4.7+		
53 I 128	− 2.02	53–75	$d_{5/2}-d_{3/2}$	5.7		
57 La 136	+ 2.1	57–79	$d_{5/2}-d_{3/2}$	4.8		
59 Pr 140	+ 2.4	59–81	$d_{5/2}-d_{3/2}$	4.2+		
(b) $\Delta I=0$, Yes (first forbidden)						
7 N 16	−10.3	7–9	$p_{1/2}-s_{1/2}$	6.9		
36 Kr 88	− 2.4	37–51	$f_{5/2}-d_{5/2}$	6.8		
37 Rb 88	− 4.6	37–51	$f_{5/2}-d_{5/2}$	7.0		
54 Xe 138	− 2.68	55–83	$g_{7/2}-f_{7/2}$	6.5		
58 Ce 144	− 0.30	59–85	$g_{7/2}-f_{7/2}$	7.2		
59 Pr 142	− 2.22	59–83	$g_{7/2}-f_{7/2}$	7.8		
81 RaE″ 206	− 1.70	81–125	$s_{1/2}-p_{1/2}$	5.5		
(c) $\Delta I=2$, Yes (first forbidden)						
17 Cl 38	− 4.81	17–21	$d_{3/2}-f_{7/2}$	7.4	9.6	
19 K 42	− 3.58	19–23	$d_{3/2}-f_{7/2}$	8.0	9.8	
33 As 76	− 3.04	33–43	$f_{5/2}-g_{9/2}$	8.3	10.0	
37 Rb 86	− 1.82	37–49	$f_{5/2}-g_{9/2}$	8.3	9.5	
38 Sr 90	− 0.53	39–51	$p_{1/2}-d_{5/2}$	9.2	9.7	
39 Y 90	− 2.18	39–51	$p_{1/2}-d_{5/2}$	8.0	9.5	
39 Y 92	− 3.5	39–53	$p_{1/2}-d_{5/2}$	7.9+	9.7	
41 Nb 94*m*	− 1.3	41–53	$p_{1/2}-d_{5/2}$	7.4	8.5	
45 Rh 102	+ 1.13	45–57	$p_{1/2}-d_{5/2}$	7.7+	8.6	
	− 1.04			8.7+	9.6	
59 Pr 142	− 2.22	59–83	$g_{7/2}-f_{7/2}$	7.8	8.1	
69 Tm 170	− 0.97	69–101	$s_{1/2}-f_{5/2}$	8.9	9.8	
81 Tl 204	− 0.78	81–123	$s_{1/2}-p_{3/2}$	9.6	10.4	
83 RaE 210	− 1.17	83–127	$h_{9/2}-d_{5/2}$	8.0	9.0	
(d) $\Delta I=1$; No, $\Delta l=2$ (l-forbidden)						
6 C 14	− 0.156	7–7	$p_{1/2}-p_{1/2}$	9.0		1
15 P 32	− 1.71	15–17	$s_{1/2}-d_{3/2}$	7.9		
29 Cu 60	+ 3.3	29–31	$p_{3/2}-f_{5/2}$	7.1+		
29 Cu 64	− 0.66	29–35	$p_{3/2}-f_{5/2}$	5.0		
	+ 0.57			5.4		
31 Ga 68	+ 1.9	31–37	$p_{3/2}-f_{5/2}$	5.1		
51 Sb 122	− 1.94	51–71	$d_{5/2}-g_{7/2}$	7.9+		
53 I 126	− 1.27	53–73	$d_{5/2}-g_{7/2}$	7.6		
(e) $\Delta I=2$; No, or $\Delta I>2$ (second and higher forbidden)						
4 Be 10	− 0.56	5–5	$p_{3/2}-p_{3/2}$	13.7		*3*
11 Na 22	+ 1.86	11–11	$D_{3/2}-D_{3/2}$	14.0		*3*
17 Cl 36	− 0.71	17–19	$d_{3/2}-d_{3/2}$	13.5		*2*
19 K 40	− 1.36	19–21	$d_{3/2}-f_{7/2}$	17.6		*4*

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[3] E. Feenberg and G. Trigg, Revs. Modern Phys. **22**, 399 (1950).

next case is P^{32} with 7.9. No first-forbidden interpretation (i.e., change in parity) is possible for this nucleus, while a spin change of 2 with no parity change would lead to the expectation of a much higher *ft* value. An experimental determination of the spin of P^{32} would thus be particularly interesting. Cu^{60}, Sb^{122}, and I^{126} have *ft* values compatible with first-forbidden transitions but with neutron and proton configuration in the same shell, which should exclude a change in parity. Cu^{64} and Ga^{68} have *ft* values which classify their decays as allowed. However, it cannot be ruled out that their configuration is $p_{3/2}$–$p_{3/2}$ with violation of rule (3).

The data on these nuclei, in which the transition occurs within the same shell, suggest strongly that they form a distinct group which is neither allowed nor second forbidden. An appropriate name for this class may be "*L*-forbidden." The log *ft* values of these nuclei fluctuate widely from seemingly allowed values in the neighborhood of 5 to 9 for C^{14}. It seems thus that a remnant of our selection rule is operative and that it is very much a matter of chance how far it is violated. We are thus inclined to consider the long lifetime of C^{14} as an accident.

The nuclei with series γ-rays find in most cases an unforced interpretation by rule (3). An outstanding group of this type is that with Z between 21 and 27 which have the interpretation $f_{7/2}$–$f_{7/2}$ or $f_{7/2}$–$p_{3/2}$ and which go without exception to excited states. It is unfortunately not possible to obtain reliable information about the actual spins of nuclei which fall under rule (3). In B^{10}, N^{14}, Na^{22} the spins of the neutron and proton groups are known to be parallel. For Cl^{36} a spin of 2 has been reported.[4] The evidence seems, however, not to be absolutely forcing, and the shape of the β-spectrum[5, 6] is in doubt.

For many other nuclei the decay schemes indicate high values of the spin in view of the presence of more than one γ-ray in series. Examples are Na^{24}, Sc^{48}, Ti^{48}, Mn^{52}, Co^{60}, Br^{82}, I^{130}, Cs^{134}. We believe, therefore, that in general the spins in this group are quite high and may result from a parallel coupling of neutron and proton spins, though this is probably not true in all cases.

There are some exceptions or difficulties to the scheme, which require special mention.

Li^6 has the observed spin 1, while a parallel coupling would lead to spin 3 as in B^{10}. This is not a direct contradiction to rule (3), but it seems that so low a spin in such a case is rather an exception.

Al^{26}: The decay of this nucleus belongs to Wigner's family of super-allowed transitions[7] with even *A* which is characterized by an odd-odd nucleus which could be composed by α-particles plus a deuteron. There is evidence[8] that the mass difference to Mg^{26} is higher than corresponding to the energy of the observed β-ray, so that there should be a series γ-ray. Otherwise it would have to be assumed that the two $d_{5/2}$ configurations couple to an abnormally low total spin of 1 or 0.

K^{40}: This nucleus constitutes the one definite exception to rule (2). The assignment of orbitals $d_{3/2}$–$f_{7/2}$ in this case is particularly free from ambiguity, and the magnetic moment fits well with it. Rule (2) would lead to a spin 2, while 4 is observed.

Cu^{64} and Ga^{68} have already been mentioned as possible exceptions to rule (3). There are further a number of problems arising from an incomplete knowledge of the facts. These cases are pointed out in the notes of Table II, Sec. C.

Summing up, one may say that the rules (1) to (3) seem to hold for the great majority of cases, but not without exception. This is not surprising in view of the great complexity of the situation. Nevertheless, they provide apparently an excellent key to the understanding of the β-transitions of even *A* nuclei.

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[4] C. H. Townes and L. G. Aamodt, Phys. Rev. **76**, 691 (1949).

[5] C. S. Wu and L. Feldman, Phys. Rev. **76**, 693 (1949).

[6] H. W. Fulbright and J. C. D. Milton, Phys. Rev. **82**, 274 (1951).

[7] The other members of this group are He^6, F^{18}, which go to the ground state, and C^{10} and O^{14}, which go to excited states of the daughter nuclei.

[8] K. Way (private communication).

C. TABLES FOR β-DECAY SYSTEMATICS: EVEN *A* (TABLE II)

TABLE II. Beta-decay data and orbital assignments for even-*A* nuclei.

Column 1: Class of transition: A. isotope certain; B. isotope probable; C. isotope doubtful. Class C. nuclei are only included if the β-decay data contribute to the identification. a. decay data well established; b. decay data probably correct; c. decay data uncertain and possibly incorrect; α. configuration assignment well established; β. configuration assignment probable; γ. configuration assignment uncertain and possibly incorrect. Column 2: Initial isotope: Z-Element-A. The *m* denotes a *meta*stable state. Column 3: Sign of emitted charge, maximum energy in Mev of the most energetic observed β-ray. The energy is given in brackets, if the transition is believed to go to an excited state. Column 4: Half-life. Column 5: *g*, *e*, *m*, mean, respectively, transition is believed to go to the ground, an excited, or a *meta*stable state of the final nucleus. The figure following gives the branching percentage to the specified state when known. The 100 means that there is a branching, but of unknown percentage. Omission of a figure means that most of the transitions go to the specified state. Column 6: Proton and neutron numbers in this order for the odd-odd nucleus involved in the transition. Column 7: Assignment of orbitals to the odd proton and the odd neutron in the odd-odd nucleus. Column 8: Predicted spin for the odd-odd nucleus. *h* means that the spin is higher than the difference between proton and neutron spins. Asterisk signifies that the spin has been measured. Column 9: Log *ft* value calculated with the *f* functions for allowed transitions. The values are given in brackets if the transition goes to an excited state. A plus sign is added if branching of unknown percentage is known to occur. Column 10: Reference to bibliography. No authors are quoted if all references tre given in the compilations by Seaborg (S1), Mitchell (M1), or Nat. Bur. Stand. (N1). Column 11: Reference to footnotes for table.

Class 1	Z-Element-A 2	Sign Energy 3	Half-life 4	Final state 5	Numbers 6	Configuration 7	Spin 8^a	Log *ft* 9	Ref. 10	Foot-notes 11
Aaγ	2–He–6	− 3.22	0.82 sec	*g*	3–3	$p_{3/2}$–$p_{3/2}$	1*	2.8	P1	
Aaα	3–Li–8	−(13)	0.89 sec	*e*<100	3–5	$p_{3/2}$–$p_{3/2}$	*h*	(5.6+)	H1	b
Aaα	4–Be–10	− 0.56	2.7×10^6 yr	*g*	5–5	$p_{3/2}$–$p_{3/2}$	3*	13.7	H2	
Aaα	5–B–12	− 13.4	0.027 sec	*g*	5–7	$p_{3/2}$–$p_{1/2}$	1	4.2	H1	
Abα	6–C–10	+(2.2)	19.1 sec	*e*	5–5	$p_{3/2}$–$p_{3/2}$	3*	3.3	S1	c
Aaβ	6–C–14	− 0.156	5720 yr	*g*	7–7	$p_{1/2}$–$p_{1/2}$	1*	9.0	E1	d
Bbα	7–N–12	+16.6	0.0125 sec	*g*	7–5	$p_{1/2}$–$p_{3/2}$	1	4.1	A1	
Aaα	7–N–16	−10.3	7.35 sec	*g*18	7–9	$p_{1/2}$–$s_{1/2}$	0	6.9	B1	
Baβ	8–O–14	+(1.8)	76 sec	*e*	7–7	$p_{1/2}$–$p_{1/2}$	1*	(3.5)	S1	c
Abα	9–F–18	+ 0.63	112 min	*g*<100	9–9	$s_{1/2}$–$s_{1/2}$	1	3.6+	B2	e
Abβ	9–F–20	−(5.01)	12 sec	*e*	9–11	$s_{1/2}$–$D_{3/2}$	1	(4.9)	S1	f
Abβ	11–Na–22	+ 1.86	30 yr	*g*0.005	11–11	$D_{3/2}$–$D_{3/2}$	3*	14.0	M2	f
Aaβ	11–Na–24	−(1.39)	14.9 hr	*e*	11–13	$d_{5/2}$–$d_{5/2}$	*h*	(6.1)	M1	g
Acγ	13–Al–26	−(2.99)	6.3 sec	*e*	13–13	$d_{5/2}$–$d_{5/2}$	*h*	(3.3)	S1	h
Aaβ	13–Al–28	−(3.01)	2.3 min	*e*	13–15	$d_{5/2}$–$s_{1/2}$	*h*	(5.0)	M1	
Abα	15–P–30	+ 3.5	2.55 min	*g*	15–15	$s_{1/2}$–$s_{1/2}$	1	5.0	S1	i
Aaβ	15–P–32	− 1.71	14.1 days	*g*	15–17	$s_{1/2}$–$d_{3/2}$	1	7.9	S1	i
Bbβ	15–P–34	− 5.1	12.4 sec	*g*75	15–19	$d_{5/2}$–$d_{3/2}$	1	4.7	S1	i
Acα	17–Cl–34	+(5.1)	33 min	*e*80	17–17	$d_{3/2}$–$d_{3/2}$	*h*	(7.0)	H3	j
Aaα	17–Cl–36	− 0.71	4.4×10^5 yr	*g*	17–19	$d_{3/2}$–$d_{3/2}$	2*	13.5	W1	k
Aaα	17–Cl–38	− 4.81	38 min	*g*53	17–21	$d_{3/2}$–$f_{7/2}$	2	7.4	L1	
Abα	19–K–38	+(2.53)	7.5 min	*e*	19–19	$d_{3/2}$–$d_{3/2}$	*h*	(4.8)	S1	
Aaγ	19–K–40	− 1.36	4×10^8 yr	*g*	19–21	$d_{3/2}$–$f_{7/2}$	4*	17.6	A2, B3	l
Aaα	19–K–42	− 3.58	12.4 hr	*g*75	19–23	$d_{3/2}$–$f_{7/2}$	2	8.0	M1	
Acβ	21–Sc–44	+(1.33)	3.92 hr	*e*<33	21–23	$f_{7/2}$–$f_{7/2}$	*h*	(5.5)	H4	
Aaβ	21–Sc–46	−(1.49)	85 days	*e*2	21–25	$f_{7/2}$–$f_{7/2}$	*h*	(10.2)	M1	m
Abα	21–Sc–48	−(0.64)	44 hr	*e*	21–27	$f_{7/2}$–$f_{7/2}$	*h*	(5.4)	M1	
Abβ	23–V–48	+(0.72)	16 days	*e*58	23–25	$f_{7/2}$–$f_{7/2}$	*h*	(6.2)	M1	m
Abβ	23–V–52	−(2.05)	3.9 min	*e*<100	23–29	$f_{7/2}$–$p_{3/2}$	*h*	(4.4)	M1	
Aaβ	25–Mn–52	+(0.58)	6.5 days	*e*50	25–27	$f_{7/2}$–$f_{7/2}$	*h*	(5.1)	M1	m
Aaβ	25–Mn–56	−(2.81)	2.5 hr	*e*50	25–31	$f_{7/2}$–$p_{3/2}$	*h*	(7.1)	M1	m
Acβ	26–Fe–52	+(0.55)	7.8 hr	*e*<100	25–27	$f_{7/2}$–$f_{7/2}$	*h*	(3.7+)	S1	n
Abα	27–Co–56	+(1.48)	80 days	*e*<100	27–29	$f_{7/2}$–$p_{3/2}$	*h*	(8.1+)	M1	
Abα	27–Co–58	+(0.47)	72 days	*e*15	27–31	$f_{7/2}$–$p_{3/2}$	*h*	(6.6)	M1	
Aaα	27–Co–60	−(0.31)	5.3 yr	*e*	27–33	$f_{7/2}$–$p_{3/2}$	*h*	(7.5)	M1	
Bbβ	27–Co–62	−(2.3)	13.9 min	*e*	27–35	$f_{7/2}$–$p_{3/2}$	*h*	(5.4)	P2	
Abα	29–Cu–60	+ 3.3	24.6 min	*g*5	29–31	$p_{3/2}$–$f_{5/2}$	1	7.1	S1	o
Acβ	29–Cu–62	+(2.83)	10.1 min	*e*	29–33	$p_{3/2}$–$p_{3/2}$	*h*	(5.1)	B5	
Aaγ	29–Cu–64	− 0.66	13 hr	*g*18	29–35	$p_{3/2}$–$f_{5/2}$	1	5.0	B6	p
		+ 0.57		*g*35				5.4		
Abβ	29–Cu–66	−(2.58)	5 min	*e*	29–37	$p_{3/2}$–$f_{5/2}$	1	(5.2)	N1	
Abβ	30–Zn–62	+(0.665)	9.2 hr	*e*10	29–33	$p_{3/2}$–$p_{3/2}$	*h*	(5.1)	H5	
Acβ	30–Zn–72	−(1.6)	49 hr	*e*5	31–41	$p_{3/2}$–$g_{9/2}$	*h*	(8.5)	S1	q
Abβ	31–Ga–66	+(4.14)	9.4 hr	*e*29	31–35	$p_{3/2}$–$p_{3/2}$	*h*	(8.0)	M3	
Abγ	31–Ga–68	+ 1.9	68 min	*g*<100	31–37	$p_{3/2}$–$f_{5/2}$	1	5.1+	S1	r
Abα	31–Ga–70	− 1.65	20 min	*g*	31–39	$p_{3/2}$–$p_{1/2}$	1	5.0	S1	
Aaα	31–Ga–72	−(3.17)	14.3 days	*e*8	31–41	$p_{3/2}$–$g_{9/2}$	*h*	(9.0)	M1	
Bbβ	33–As–72	+(2.78)	26 hr	*e*33	33–39	$f_{5/2}$–$p_{1/2}$	*h*	(7.3)	M4	s
Aaα	33–As–76	− 3.04	26.8 hr	*g*60	33–43	$f_{5/2}$–$g_{9/2}$	2	8.3	M1	t
Acβ	35–Br–78	+ 2.3	6.4 min	*g*<100	35–43	$p_{3/2}$–$p_{1/2}$	1	4.4+	S1	u
Abα	35–Br–80	+ 0.7	18 min	*g*<3	35–45	$p_{3/2}$–$p_{1/2}$	1	4.3+	N1	
		− 2.0		*g*97				5.4	N1	
Abβ	35–Br–82	−(0.447)	36 hr	*e*<100	35–47	$p_{3/2}$–$g_{9/2}$	*h*	(5.1)	M1	
Abα	36–Kr–88	− 2.4	2.8 hr	*g*	37–51	$f_{5/2}$–$d_{5/2}$	0	6.8	K1	
Aaα	37–Rb–86	− 1.82	19.5 days	*g*80	37–49	$f_{5/2}$–$g_{9/2}$	2	8.3	M1	

TABLE II—*Continued.*

Class 1	Z-Element-A 2	Sign Energy 3	Half-life 4	Final state 5	Numbers 6	Configuration 7	Spin 8[a]	Log *ft* 9	Ref. 10	Foot-notes 11
Abα	37–Rb–88	− 4.6	17.5 min	g	37–51	$f_{5/2}-d_{5/2}$	0	7.0	S1	
Aaα	38–Sr–90	− 0.53	25 yr	g	39–51	$p_{1/2}-d_{5/2}$	2	9.2	J1	
Aaβ	39–Y–88	+(0.83)	105 days	$e0.2$	39–49	$p_{1/2}-g_{9/2}$	4	(9.6)	M1	
Aaα	39–Y–90	− 2.18	65 hr	g	39–51	$p_{1/2}-d_{5/2}$	2	8.0	L2	
Acα	39–Y–92	− 3.5	3.5 hr	$g<100$	39–53	$p_{1/2}-d_{5/2}$	2	7.9+	S1	v
Abβ	41–Nb–92	−(1.38)	10.1 days	e	41–51	$g_{9/2}-d_{5/2}$	h	(7.7)	S1	w
Abβ	41–Nb^m–94	− 1.3	6.6 min	$g0.1$	41–53	$p_{1/2}-d_{5/2}$	2	7.4	S1	
Bbβ	41–Nb–96	−(0.67)	23.3 hr	e	41–55	$g_{9/2}-d_{5/2}$	h	(5.6)	K2	x
Abα	44–Ru–106	− 0.039	1.0 yr	g	45–61	$g_{9/2}-g_{7/2}$	1	4.3	A3	
Abα	45–Rh–102	+ 1.13	210 days	$g<100$	45–57	$p_{1/2}-d_{5/2}$	2	7.7+	S1	
		− 1.04		$g<100$				8.7+	S1	
Abβ	45–Rh–104	− 2.6	44 sec	$g<100$	45–59	$g_{9/2}-g_{7/2}$	1	4.7+	N1	y
Aaα	45–Rh–106	− 3.55	30 sec	$g82$	45–61	$g_{9/2}-g_{7/2}$	1	5.2	M1	
Aaα	46–Pd–112	− 0.2	21 hr	g	47–65	$g_{9/2}-g_{7/2}$	1	4.0	S1	z
Aaα	47–Ag–106	+ 2.04	24.5 min	$g<100$	47–59	$g_{9/2}-g_{7/2}$	1	4.7+	S1	
Abα	47–Ag–108	− 2.8	2.3 min	g	47–61	$g_{9/2}-g_{7/2}$	1	5.3	S1	
Aaα	47–Ag–110	− 2.86	24 sec	$g<100$	47–63	$g_{9/2}-g_{7/2}$	1	4.7+	S2	
Aaβ	47–Ag^m–110	−(0.53)	225 days	e	47–63	$p_{1/2}-g_{7/2}$	h	(7.6)	S2	
Abα	49–In–110	+ 1.6	65 min	$g<100$	49–61	$g_{9/2}-g_{7/2}$	1	4.7+	S1	
Aaα	49–In–114	− 1.98	72 sec	$g96$	49–65	$g_{9/2}-g_{7/2}$	1	4.4	M5	
Aaα	49–In–116	− 2.8	13 sec	g	49–67	$g_{9/2}-g_{7/2}$	1	4.4	S1	
Abβ	59–In^m–116	−(0.85)	54 min	e	49–67	$p_{1/2}-g_{7/2}$	h	(4.7+)	S1	
Bbβ	49–In–118	− 1.5	4.5 min	$g<100$	49–69	$g_{9/2}-g_{7/2}$	1	4.7+	D1	aa
Abβ	51–Sb–122	− 1.94	2.6 days	$g<100$	51–71	$d_{5/2}-g_{7/2}$	1	7.9+	M1	bb
Aaβ	51–Sb–124	−(2.37)	60 days	$e21$	51–73	$g_{7/2}-s_{1/2}$	3	(10.3)	M1	cc
Bbβ	52–Te–132	−(0.36)	77 hr	e	53–79	$g_{7/2}-d_{3/2}$	h	(5.4)	S1	dd
Aaβ	53–I–124	+(2.20)	4 days	$e<50$	53–71	$d_{5/2}-s_{1/2}$	h	(7.6+)	M1	ee
Aaβ	53–I–126	− 1.27	13 days	$g27$	53–73	$d_{5/2}-g_{7/2}$	1	7.6	M1	ff
Aaα	53–I–128	− 2.02	25 min	$g93$	53–75	$d_{5/2}-d_{3/2}$	1	5.7	M1	
Aaβ	53–I–130	−(1.03)	12.6 hr	$e60$	53–77	$g_{7/2}-d_{3/2}$	h	(6.4)	M1	
Bbβ	54–Xe–138	− 2.68	30 min	g	55–83	$g_{7/2}-f_{7/2}$	0	6.5	T1	
Aaβ	55–Cs–134	−(0.66)	2.3 yr	$e75$	55–79	$g_{7/2}-d_{3/2}$	h	(8.9)	M1	
Abβ	55–Cs–136	−(0.28)	13 days	e	55–81	$g_{7/2}-d_{3/2}$	h	(5.8)	S1	
Acγ	56–Ba–140	− 1.02	12.8 days	$g60?$	57–83	$d_{5/2}-f_{7/2}$	h	7.9	M1	gg
Abα	57–La–136	+ 2.1	9.5 min	$g33$	57–79	$d_{5/2}-d_{3/2}$	1	4.8	N2	
Aaβ	57–La–140	−(2.26)	40 hr	$e10$	57–83	$d_{5/2}-f_{7/2}$	h	(9.1)	M1	gg
Aaβ	58–Ce–144	− 0.30	275 days	g	59–85	$g_{7/2}-g_{7/2}$	0	7.2	S1	
Abγ	59–Pr–140	+ 2.4	3.5 min	$g<100$	59–81	$d_{5/2}-d_{3/2}$	1	4.2+	S1	
Abγ	59–Pr–142	− 2.22	19.3 hr	$g98$	59–83	$g_{7/2}-f_{7/2}$	0	7.8	M6	hh
Aaγ	65–Tb–160	−(0.86)	71 days	$e42$	65–95	$d_{5/2}-f_{7/2}$	h	(8.6)	B7	ii
Abγ	69–Tm–170	− 0.97	127 days	$g90$	69–101	$s_{1/2}-f_{5/2}$	2	8.9	M1	
Abβ	71–Lu–176	−(0.4)	2.4×10^{10} yr	$e33$	71–105	$g_{7/2}-h_{9/2}$	>7*	(18.9)	S1	jj
Abγ	73–Ta–182	−(0.53)	113 days	e	73–109	$g_{7/2}-p_{3/2}$	2	(8.0)	B4	kk
Abγ	75–Re–186	−(1.07)	90 hr	e	75–111	$d_{3/2}-p_{1/2}$	h	(7.5)	M1	
Abγ	79–Au–192	+(1.9)	4.0 hr	$e1$	79–113	$d_{3/2}-p_{1/2}$	2	(7.4)	W2	kk
Bbγ	79–Au–194	+(1.8)	39.5 hr	$e3$	79–115	$d_{3/2}-p_{1/2}$	2	(7.9)	W2	kk
Aaγ	79–Au–196	−(0.30)	5.6 days	$e5$	79–117	$d_{3/2}-p_{1/2}$	2	(7.3)	S3	kk
Aaγ	79–Au–198	−(0.97)	2.8 days	e	79–119	$d_{3/2}-p_{1/2}$	2	(7.3)	M1	
Aaβ	81–Tl–204	− 0.78	3 yr	g	81–123	$s_{1/2}-p_{3/2}$	2	9.6	S4	ll
Aaβ	81–RaE″–206	− 1.70	4.25 min	g	81–125	$s_{1/2}-p_{1/2}$	0	5.5	F1	mm
Abγ	81–ThC″–208	−(1.79)	3.1 min	$e33$	81–127	$s_{1/2}-g_{9/2}$	h	(5.8)	F1	
Abγ	81–RaC″–210	−(1.88)	1.32 min	e	81–129	$s_{1/2}-g_{9/2}$	h	(5.1)	F1	
Abγ	82–RaD–210	−(0.029)	22 yr	e	83–127	$h_{9/2}-d_{5/2}$	2	(6.1)	C1	
Aaγ	83–RaE–210	− 1.17	5.0 days	g	83–127	$h_{9/2}-d_{5/2}$	2	8.0	S1	

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[a] Asterisk signifies that the spin has been measured.

[b] The transition goes preferentially to an excited state of Be^8 which decays directly into two He^4 nuclei.

[c] Superallowed into an excited state.

[d] C^{14} represents an extreme l-forbidden case. O^{14}, which goes into the same product nucleus N^{14} has a superallowed transition via an excited state.

[e] Superallowed.

[f] It cannot be decided whether the configurations for 11 nucleons are $D_{3/2}$ or $d_{5/2}$.

[g] This transition is certainly high forbidden since there are two γ-rays in cascade. It cannot be decided whether in this case a $D_{3/2}$ configuration for the 11 protons couples with the $d_{3/2}$ neutrons to a high spin, or whether the protons also have a $d_{5/2}$ configuration.

[h] The empirical data for Al^{26} suggests a series γ-ray and thus a superallowed transition to an excited state.

[i] The three P isotopes furnish an instructive example for the working of the shell scheme. All three must be assumed to have spin 1. P^{32} is l-forbidden. The orbital for the 15 protons in P^{34} has to be assumed to be $d_{5/2}$ to explain the allowed character of its decay. An alternative interpretation is $s_{1/2}-s_{1/2}$.

[j] The shell scheme suggests strongly a series γ-ray for this transition, which is by no means excluded by the experimental evidence. The coupling rule in its narrower form demands, of course, only that the spin is 0.

[k] Lifetime and shape of spectrum both suggests a spin 3 for Cl^{36}, while the reported evidence for spin 2 does not seem to be forcing.

[l] K^{40} constitutes the most notable exception to the spin rule, which would predict a spin of 2 in place of the observed 4. The alternative possible configuration $s_{1/2}-f_{7/2}$ would give a spin 4, but would make it difficult to explain the observed magnetic moment.

[m] It cannot be decided whether the configurations of 25 nucleons are $F_{5/2}$ or $f_{7/2}$. They couple with $f_{7/2}$ and $p_{3/2}$ opposites always to a high resultant spin.

[n] Insufficient experimental evidence.

[o] Experimental evidence insufficient. However, $f_{5/2}$ orbits for the odd neutrons seem to occur in other Ni isotopes.

[p] Cu^{64} presents a definite difficulty for the shell scheme. The interpretation of the table ($p_{3/2}-f_{5/2}$) makes its transition l-forbidden with an abnormally low ft value. The natural $p_{3/2}-p_{3/2}$ combination should lead to a high resultant spin according to the composition rule.

[q] This transition should be highly forbidden since this is also the case for the odd-odd product nucleus Ga^{72}.

[r] This not too well-investigated isotope poses a difficulty. The transition either shows an abnormally low ft value for its l-forbidden character or would involve the anomalous occurrence of a $p_{1/2}$ orbit in place of $f_{5/2}$. A series γ-ray would eliminate the problem.

[s] A series γ-ray is reported for this transition, which is thus empirically high forbidden. The $f_{5/2}$ orbit for the 33 protons is somewhat uncomfortable, but so would be the alternative $p_{3/2}-g_{9/2}$.

[t] This assignment is strongly supported by the shape of the β-spectrum.

(*Footnotes continued on next page.*)

[u] Evidence not sufficient to decide whether the γ-rays of this transition are in parallel or in series. The interpretation in the latter case would be $p_{3/2}$–$g_{9/2}$ with probable spin 3.

[v] γ-ray probably not in series.

[w] $p_{1/2}$–$d_{5/2}$ is an alternative, which would also be possible if the γ-ray should not be in series as assumed.

[x] $p_{1/2}$–$d_{5/2}$ is another possible assignment.

[y] This interpretation assumes the γ-rays to be in parallel. Several alternatives are possible if they are in series.

[z] The $g_{9/2}$–$g_{7/2}$ configurations show particularly low *ft* values. In the case of Pd^{112} the energy is not too accurately known.

[aa] Insufficient evidence about the occurring γ-radiation.

[bb] The more natural $d_{5/2}$–$s_{1/2}$ combination would give a too highly forbidden transition. A possible alternative is $g_{7/2}$–$h_{11/2}$ with spin 2.

[cc] The assignment of the ground state of Sb^{124} is made on basis of spin 7/2 for Sb^{123} and spin 1/2 for Te^{123}. An attempt to interpret the complex situation presented by the two *meta*stable states of Sb^{124} would seem to be premature.

[dd] The interpretation would be $d_{5/2}$–$d_{3/2}$ if the γ-ray is not in series.

[ee] In place of $d_{5/2}$ also $g_{7/2}$ is possible.

[ff] The $g_{7/2}$ configuration for 73 neutrons is somewhat unusual but not too strange since 73 protons in Ta^{181} show a spin 7/2.

[gg] In the chain Ba^{140}–La–Ce the odd-odd nucleus is the middle one. The transition of La is certainly highly forbidden, indicating a high spin. It is then very difficult to understand why Ba^{140} is much less strongly forbidden, unless its spin is different from zero. The other alternative is that the 1.02-Mev β-ray does not go to the ground state.

[hh] According to a recent private communication by E. Jensen, Pr^{142} shows the form of the β-spectrum typical for transition with change of partity and spin change 2. This poses a somewhat difficult problem. A possibility suggested by Jensen is $d_{5/2}$–$h_{9/2}$. However, this means a change of orbital momentum by 3, which one would expect to lead to considerably higher *ft* values.

[ii] Most interpretations from here on are very tentative, owing to the absence of spin data for high neutron numbers.

[jj] The combination given is the only one which gives a high enough spin. The *ft* value for this β-decay, although very large, is considerably less than expected for the transition to the Hf^{176} ground state involving a spin change of 7.

[kk] The γ-rays in these transitions are all assumed to be in series.

[ll] Alternatives are $d_{3/2}$–$p_{1/2}$ and $s_{1/2}$–$f_{5/2}$.

[mm] The low *ft* value for a first-forbidden transition may be explained on the basis of the high Z value; compare Konopinski, Revs. Modern Phys. **15**, 209 (1943).

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