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Sargent Diagram and Comparative Half-Lives for K-Electron Capture Transitions of Odd Nuclides (with $Z \leq 60$)

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Modified Sargent diagram of K-electron capture transitions of odd nuclides with $Z \leq 60$ shows an allowed transition band with superallowed transitions well above the first-forbidden transitions below it. Correspondingly the histogram of log*ft* values of these transitions shows a peak in the range of 5 to 6.

PREVIOUS study of the Sargent diagram for electron capture transitions in heavy nuclides ($89 \leq Z \leq 98$) showed that points group along two lines which can be identified as allowed and forbidden transitions.[1,2] When the diagram was extended to the region of light and medium nuclides, the points scattered and did not permit differentiation of Sargent curves for different degrees of forbiddenness.[3] However, the distribution of log*ft* values for these electron-capture transitions showed a peak in the range of 5 to 6,[3] corresponding to the allowed unfavored group observed in β-decay processes.[4]

In the present study we have tried to reduce the scatter by normalizing the transition probability per unit time to equal chance of finding an orbital electron at the nuclear surface for various elements. The theoretical transition probability per unit time for allowed K-electron capture is given by[5]

$$\lambda_K = \frac{G^2}{4\pi^2} |\mathfrak{M}|^2 g_K{}^2 W_K{}^2, \tag{1}$$

where G is the Fermi constant, $\mathfrak{M}$ the nuclear matrix element, g_K the "large" component of Dirac Coulomb wave function for K-electron evaluated at the nuclear surface, and W_K the transition energy for K-capture. The f-factor for the estimation of comparative half-life of allowed K-capture transition is given by[4]

$$f = \frac{\pi}{2} g_K{}^2 W_K{}^2, \tag{2}$$

so that

$$\log ft = \log(\pi \ln 2^{\frac{1}{2}}) + \log g_K{}^2 + \log W_K{}^2 - \log \lambda_K, \tag{3}$$

where t is the partial half-life for the K-capture transition. Equation (3) gives the relation between transition probability, comparative half-life and transition energy. The Dirac Coulomb wave function g_K can be approximated by the simple function[3]

$$\log g_K{}^2 = (7.9776 - 10) + 0.03256Z - 10^{(0.48775 - 0.0380236Z)} \tag{4}$$

to within 2% accuracy in the region $4 \leq Z \leq 60$. In this paper the normalized transition probability per unit time $\lambda_K / g_K{}^2$ for K-capture is plotted against the transition energy W_K.

In Table I forty-eight electron-capture transitions are tabulated, following the form of Major and Bieden-

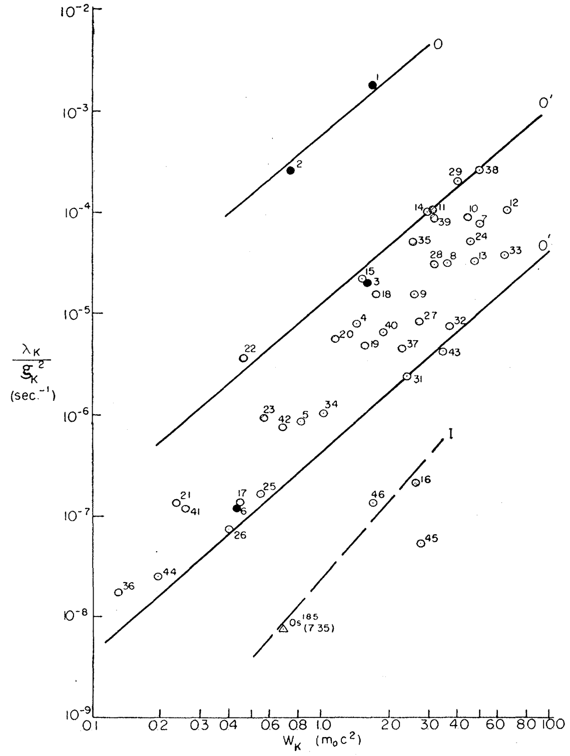

FIG. 1. Modified Sargent diagram for K-electron capture transitions of odd nuclides (with Z-60). Dot indicates that the transition belongs to class A; shaded circles are class B; and circles are class C.

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[1] S. G. Thompson, Phys. Rev. **76**, 319 (1949).

[2] N. Feather, *Nuclear Stability Rules* (Cambridge University Press, London, 1952), p. 108.

[3] J. K. Major and L. C. Biedenharn, Revs. Modern Phys. **26**, 321 (1954).

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

[5] Bouchez, de Groot, Nataf, and Tolhoek, J. phys. radium **11**, 105 (1950).

Table I. Values of λ_k/g_k^2 and log*ft* for *K*-electron capture transitions of odd nuclides (with $Z \leq 60$).[a]

1	2	3	4	5	6	7	8	9	10	11		12	13	14
										Shell model				
No.	Element	Class	Half-life	%*K*	Reference	λ_k (sec^{-1})	$w_k(m_0c^2)$	Reference	Final state	Initial	Final	Reference	λ_k (sec^{-1})$/g_k^2$	log*ft*
1	4 Be 7	*A*	52.93 days	89	b	1.35 10^{-7}	1.69	b	c	$p_{3/2}$	$p_{3/2}$	c	1.42 10^{-3}	3.30
2		*A*		11	b	1.67 10^{-8}	0.75	b	*e*	$p_{3/2}$	$p_{1/2}$	c	1.76 10^{-4}	3.47
3	18 A 37	*A*	34.1 days	92	b	2.16 10^{-7}	1.59	b	*g*	$d_{3/2}$	$d_{3/2}$	c	1.90 10^{-5}	4.95
4	24 Cr 51	*C*	27.75 days	90	d	2.61 10^{-7}	1.46	d	*g*	$f_{7/2}$	$f_{7/2}$	d	7.75 10^{-6}	5.28
5		*C*		10	d	2.89 10^{-8}	0.83	d	*e*	$f_{7/2}$	$f_{5/2}$	d	8.58 10^{-7}	5.74
6	26 Fe 55	*A*	2.94 years	100	b	7.48 10^{-9}	0.44	b	*g*	$p_{3/2}$	$f_{5/2}$	c	1.10 10^{-7}	6.06
7	27 Co 55	*C*	18.2 hr	39	b	4.12 10^{-6}	4.93	b	*e*	$f_{7/2}$	$f_{5/2}$	e,f	7.71 10^{-5}	5.35
8	28 Ni 57	*C*	36.2 hr	36	b	1.92 10^{-6}	3.65	b	*e*	$p_{3/2}$	$p_{3/2}$	g	3.20 10^{-5}	5.46
9		*C*		14	g	7.50 10^{-7}	2.58	g	*e*	$p_{3/2}$			1.25 10^{-5}	5.57
10	29 Cu 61	*B*	3.35 hr	16	b	9.28 10^{-6}	4.37	b	*g*	$p_{3/2}$	$f_{5/2}$	c	9.00 10^{-5}	5.11
11		*B*		13	b	7.41 10^{-6}	3.08	b	*e*	$p_{3/2}$	$p_{3/2}$	h	1.08 10^{-4}	4.72
12	30 Zn 63	*C*	38.3 min	2.8	b	8.43 10^{-6}	6.64	b	*g*	$p_{3/2}$	$p_{3/2}$	c	1.09 10^{-4}	5.44
13		*C*		0.8	b	2.52 10^{-6}	4.75	b	*e*	$p_{3/2}$			3.28 10^{-5}	5.67
14		*C*		2.8	b	8.43 10^{-6}	2.98	b	*e*	$p_{3/2}$			1.09 10^{-4}	4.78
15		*C*		0.6	b	1.68 10^{-6}	1.53	i	*e*	$p_{3/2}$			2.18 10^{-5}	4.90
16	30 Zn 65	*B*	245 days	54	b	1.77 10^{-8}	2.65	b	*g*	$f_{5/2}$	$p_{3/2}$	c	2.29 10^{-7}	7.26
17		*B*		43	b	1.41 10^{-8}	0.44	b	*e*	$f_{5/2}$	$f_{7/2}$	j	1.38 10^{-7}	5.98
18	31 Ga 67	*B*	77.9 hr	55	b	1.36 10^{-6}	1.76	b	*e*	$p_{3/2}$	$p_{3/2}$	k	1.53 10^{-5}	5.15
19		*B*		25	b	6.20 10^{-7}	1.58	b	*e*	$p_{3/2}$	$f_{5/2}$	k	4.66 10^{-6}	5.57
20		*B*		20	b	4.94 10^{-7}	1.17	b	*e*	$p_{3/2}$	$p_{3/2}$	k	5.57 10^{-6}	5.25
21		*B*		0.5	b	1.2 10^{-8}	0.23	b	*e*	$p_{3/2}$	$p_{3/2}$	k	1.35 10^{-7}	5.5
22	32 Ge 71	*B*	11.4 days	100	b	7.03 10^{-7}	0.46	b	*g*	$p_{1/2}$	$p_{3/2}$	c	3.53 10^{-6}	4.66
23	33 As 73	*B*	76 days	100	b	1.06 10^{-7}	0.57	b	*e*	$p_{3/2}$	$p_{3/2}$	l	9.39 10^{-7}	5.38
24	34 Se 73	*C*	7.1 hr	25	m	6.85 10^{-6}	4.55	m	*e*	$(g_{9/2})$	$(g_{9/2})$	m	5.23 10^{-5}	5.44
25	34 Se 75	*C*	127 days	35	n	2.10 10^{-8}	0.55	n	*e*	$f_{5/2}$		f	1.60 10^{-7}	6.10
26		*C*		15	n	9.50 10^{-9}	0.40	n	*e*	$f_{5/2}$		f	7.25 10^{-8}	6.18
27	35 Br 77	*B*	57 hr	35	o	1.15 10^{-6}	2.75	a	*g*	$p_{3/2}$	$p_{1/2}$	c	8.09 10^{-6}	5.81
28	36 Kr 79	*C*	34.5 hr	72	j	4.01 10^{-6}	3.17	b	*e*	$g_{7/2}$		c	2.54 10^{-5}	5.45
29	37 Rb 81	*C*	4.7 hr	35	f	1.49 10^{-5}	3.95	f	*e*	$p_{3/2}$	$p_{1/2}$	f	8.43 10^{-5}	5.12
	39 Y 87	*C*	80 hr											
31				99.7	p	2.40 10^{-6}	2.41	p	*e*	$p_{1/2}$	$p_{3/2}$	q	5.40 10^{-6}	5.81
32	40 Zr 89	*B*	79.3 hr	75	q	1.82 10^{-6}	3.78	q	*e*	$g_{9/2}$	$g_{9/2}$	c	7.29 10^{-6}	6.11
33	46 Pd 101	*C*	8 hr	90	b	2.16 10^{-5}	6.45	b	g'	$d_{5/2}$	$(g_{7/2})$	f	3.75 10^{-5}	5.89
34	46 Pd 103	*C*	17.0 days	99.9	r	4.71 10^{-7}	1.05	r	*e*	$g_{9/2}$	$g_{7/2}$	r	1.04 10^{-6}	5.86
35	48 Cd 107	*B*	6.7 hr	99.3	b	2.85 10^{-5}	2.55	b	*e*	$g_{7/2}$	$g_{7/2}$	c	5.10 10^{-5}	4.96
36	48 Cd 109	*B*	470 days	78	f	1.33 10^{-8}	0.13	f	*e*	$d_{5/2}$	$g_{7/2}$	c	1.79 10^{-8}	5.90
37	49 In 111	*B*	2.84 days	99.99	s	2.82 10^{-6}	2.31	*s*	*e*	$g_{9/2}$	$g_{7/2}$	s	4.60 10^{-6}	5.71
38	50 Sn 111	*C*	35.0 min	71	b	2.34 10^{-4}	4.96	b	*g*	$g_{7/2}$	$g_{9/2}$	c	2.75 10^{-4}	4.81
39	51 Sb 117	*B*	2.8 hr	97	t	6.70 10^{-5}	3.19	t	*e*	$d_{5/2}$	$\mathrm{D}_{3/2}$	f	8.88 10^{-5}	4.92
40	51 Sb 119	*C*	39 hr	100	f	4.95 10^{-6}	1.89	f	*e*	$d_{5/2}$	$d_{3/2}$	q	6.56 10^{-6}	5.57
41	53 I 125	*B*	60.0 days	81	f	1.09 10^{-7}	0.25	f	*e*	$d_{5/2}$	$d_{3/2}$	c	1.20 10^{-7}	5.56
42	55 Cs 131	*B*	9.6 days	100	f	8.35 10^{-7}	0.68	f	*g*	$d_{5/2}$	$d_{3/2}$	c	7.66 10^{-7}	5.62
43	58 Ce 135	*C*	22 hr	99†	b	8.66 10^{-6}	3.58	b	g'	$d_{3/2}$	$(d_{5/2})$	f	4.06 10^{-6}	6.15
44	58 Ce 139	*C*	140 days	100	f	5.73 10^{-8}	0.19	u	*e*	$d_{5/2}$	$d_{5/2}$	u	2.64 10^{-8}	5.92
45	43 Tc 95^m	*C*	60 days	28	b	3.75 10^{-8}	2.78	b,q	*g*	$p_{1/2}$	$d_{5/2}$	q	5.55 10^{-8}	7.7
46		*C*		39	b	5.22 10^{-8}	1.69	b,q	*e*	$p_{1/2}$	$s_{1/2}$	q	1.35 10^{-7}	7.1
47	20 Ca 41	*C*	1.2 10^5 years	100	b	1.83 10^{-13}	0.86	b	*g*	$f_{7/2}$	$d_{3/2}$	c	1.06 10^{-11}	10.8
48	28 Ni 59	*C*	7.5 10^4 years	100	b	2.94 10^{-13}	2.09	b	*g*	$p_{3/2}$	$f_{7/2}$	f	2.45 10^{-12}	11.9

[a] The probable assignments of even parity to the ground state of Se^{75}, odd parity to all energy levels of As^{75}, and the more branchings in the electron captures of Se^{75} may throw these two transitions out of the class of allowed transitions.

[b] J. K. Major and L. C. Biedenharn, Revs. Modern Phys. **26**, 321 (1954).

[c] K. Siegbahn, *Beta- and Gamma-Ray Spectroscopy* (Interscience Publishers, Inc., New York, 1955) p. 433.

[d] M. E. Bunker and J. W. Starner, Phys. Rev. **97**, 1272 (1955).

[e] R. S. Caird and A. C. G. Mitchell, Phys. Rev. **94**, 412 (1954).

[f] R. W. King, Revs. Modern Phys. **26**, 327 (1954).

[g] R. Canada and A. C. G. Mitchell, Phys. Rev. **83**, 955 (1951).

[h] Owen, Cook, and Owen, Phys. Rev. **78**, 686 (1950).

[i] Huber, Medicus, Preiswerk, and Steffen, Helv. Phys. Acta **20**, 495 (1947).

[j] J. K. Major, Compt. rend. **234**, 2276 (1952).

[k] Meyerhof, Mann, and West, Phys. Rev. **92**, 758 (1953).

[l] Barloutaud, Ballini, and Sartori, Compt. rend. **237**, 886 (1953).

[m] R. W. Hayward, and D. D. Hoppes, Phys. Rev. **98**, 1172 (1955).

[n] Jensen, Laslett, Martin, Hughes, and Pratt, Phys. Rev. **90**, 557 (1953).

[o] R. Sehr, Z. Phys. **137**, 528 (1954).

[p] L. G. Mann, and P. Axel, Phys. Rev. **84**, 221 (1951).

[q] M. Goldhaber, and R. D. Hill, Revs. Modern Phys. **24**, 179 (1952).

[r] B. Saraf, Phys. Rev. **97**, 715 (1955).

[s] Reference c, p. 730.

[t] C. L. McGinnis, Phys. Rev. **97**, 93 (1955).

[u] C. H. Pruett, and R. G. Wilkinson, Phys. Rev. **96**, 1340 (1954).

harn's table.[3] In column 5 the percentage of *K*-capture is corrected for branching ratio, when the disintegration is complex, and for *L*-capture, if experimentally observed. In column 13 the normalized transition probability per unit time for *K*-capture is corrected for statistical factor,[6] when the spin of the parent nucleus is smaller than that of the daughter nucleus according to the shell model prediction.

In Fig. 1 the modified Sargent diagram is plotted. It is seen that out of the forty-eight electron-capture transitions forty-one lie within a band having a width about 1.4 in logarithm scale and a slope 2 in log-log plot, with Be^7 far above and Tc^{95m} and Zn^{65} (ground-to-ground transition) far below. This can be interpreted as allowed transition band in accordance with the shell model interpretation of these transitions. The two *K*-captures of Be^7 constitute the only examples of super-

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[6] R. E. Marshak, Phys. Rev. **61**, 431 (1942).

allowed transition, while the K-captures of Tc^{95m} give the examples of first-forbidden transition. The ground-to-ground K-capture of Zn^{65} has an analomously low transition probability probably due to its L-forbidden character.[7] In the region of $4 \leq Z \leq 60$ the experimentally well-known first-forbidden transitions are rare. However, by extrapolation of $g_K{}^2$ to heavy elements the $\lambda_K/g_K{}^2$-points of the K-captures of Os^{185}, Au^{195}, Pb^{203}, At^{211}, U^{231}, Np^{235}, Pu^{237}, Am^{239}, and Bk^{243} fall well below the allowed transition band.

In Fig. 2 the histogram for the distribution of logft values is shown. It indicates three peaks at logft equal to 4.8, 5.5, and 6.0, respectively. The appearance of three peaks in this region may be illusory due to the fact that only forty-eight data have been compiled.

The highly forbidden transitions (Ca^{41} with logft $= 10.8$, Ni^{59} with log$ft = 11.9$) are too few to be included in Figs. 1 and 2.

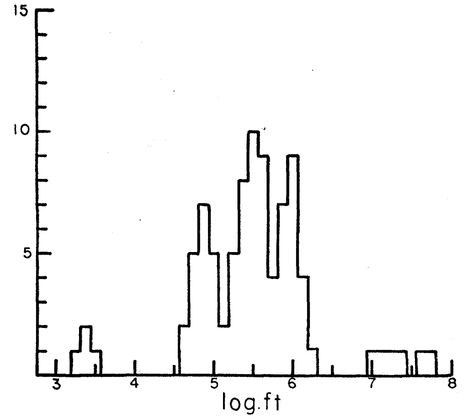

FIG. 2. Histogram of logft values for K-electron capture transitions of odd nuclides (with Z-60).

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[7] J. F. Perkins and S. K. Haynes, Phys. Rev. **92**, 687 (1953).