Unfavored Factors for Allowed β Transitions*

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Unfavored factors U, that is, ratios of computed-to-observed transition probabilities, are tabulated in a systematic manner for allowed β transitions in the strict j-j coupling scheme. The introduction of many-particle wave functions lowers the gap between favored and unfavored transitions, but does not eliminate it. The systematics brings out clearly the role of configuration interaction through a strong correlation between the U factors and the expected purity of the shell-model wave functions. The matrix elements for even-A nuclei are on the average larger than those for odd-A nuclei and thus explain without any new hypothesis the lower average ft values for the even-A group.

I. INTRODUCTION

IT is well known that the j-j coupling nuclear shell model[1] leads to an excellent systematics and classification of β-decay data.[1,2] This description is, however, of a qualitative nature. It permits, within limits, the prediction of spins and parities of nuclear ground states. However, it has not been possible to account quantitatively for the transition probabilities for β decay on the basis of the shell model. This is not too surprising, since matrix elements are a sensitive function of structure.

In particular, there is a clear experimental division of the allowed β transitions into favored transitions[3,4] (mirrors and triads) with $\log ft<4$ and other "unfavored" allowed transitions with $\log ft>4$. The shell model makes no particular distinction between these two types, whose transition probabilities differ by factors of 10 to 100.

The comparison between experimental and theoretical ft values (comparative half-lives) is usually made on the basis of single-particle wave functions. This is, however, not the correct application of the shell model, even in its extreme form. The true wave functions for the shell model are not single-particle functions, but the many-particle wave functions of lowest "seniority," [1,5] that is, maximum pairing-off of the spins of the involved particles. In the preceding paper[6] matrix elements were computed for all allowed β transitions between states of lowest seniority.

It is the purpose of this paper to give a systematic comparison for unfavored allowed transitions of the observed transition probabilities and those calculated on the basis of the shell-model wave functions. The results are expressed in "unfavored" factors U which give the ratio of the calculated to the observed transition probability. High U's thus mean small actual matrix elements.

The introduction of the many-particle shell-model wave functions generally lowers the gap between favored and unfavored transitions. It leads to interesting regularities which will be discussed in Sec. II. However, it by no means offers an explanation of the unfavored nature of most of the allowed transitions. This investigation was not undertaken to furnish such an explanation, but rather to exhibit more clearly what the consequences of the shell model are, what remains to be explained, and possibly to obtain guidance for further more detailed investigations.

It is rather fortunate that the question of the purity of the isotopic spin for the nuclear states does not play a major role in this investigation. In I the matrix elements have been evaluated for the two limiting cases, firstly that the isotopic spin is a good quantum number, and secondly that it does not play a role at all, but the proton and neutron configurations are coupled separately to their states of lowest seniority. There are some differences in the matrix elements for the case that the transition takes place in a j^N configuration, that is, both neutrons and protons end up in the same shell, but the orders of magnitude remain the same. The conclusions are thus not seriously affected. For the other class of configurations, with protons in the $j=l+\frac{1}{2}$ shell and the neutrons in the $j'=l-\frac{1}{2}=j-1$ shell, with all $l+\frac{1}{2}$ states filled, the isotopic spin happens to be a good quantum number since states with $T>T_z$ would also have to occur in the nucleus with $T_z'=T_z+1$, that is, with one less proton and one more neutron, which cannot be accom-

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[1] A recent and complete summary discussion of this model has been given by M. Goeppert Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure* (John Wiley and Sons, Inc., New York, 1955).

[2] Mayer, Moszkowski, and Nordheim, Revs. Modern Phys. **23**, 315 (1951); L. W. Nordheim, Revs. Modern Phys. **23**, 322 (1951).

[3] The special position of the mirror nuclei was first recognized by L. W. Nordheim and F. L. Yost, Phys. Rev. **51**, 942 (1937).

[4] The clarification of the nature of the "favored" or super-allowed transition is due to E. P. Wigner and was summarized by E. P. Wigner and E. Feenberg, Repts, on Progr. Phys. **8**, 274 (1941).

[5] The concept of a seniority quantum number was first introduced by G. Racah, Phys. Rev. **63**, 367 (1943).

[6] W. C. Grayson, Jr., and L. W. Nordheim, preceding paper [Phys. Rev. **102**, 1084 (1956)]; hereafter referred to as I.

modated in an $l+\frac{1}{2}$ state due to the exclusion principle. In practice, one can expect the isotopic spin to be a fairly good quantum number as long as both neutrons and protons end up in the $f_{7/2}$ shell or below. This is indicated by the fact that the transition $_{27}Co_{27}\rightarrow{}_{26}Fe_{28}$ has a log $ft=3.5$ and is thus of favored character. In cases of doubt we give in the tables the results for both assumptions.

TABLE I. Table I(A) deals with odd-A and Table I(B) with even-A nuclei. Column 1 gives the atomic number, Column 2 the transitions with neutron and proton numbers indicated. Metastable states are indicated by the superscript m, first excited states by x, second excited states by xx. Column 3 gives the log ft value. Column 4 gives the shell model interpretation. In some cases of ambiguity, two different interpretations are given. The symbols $(l_j)_T{}^N$ for odd N signify N particles all in the same orbital state j, l with resultant spin $J=j$ and isotopic spin $T=|T_z|$. The symbol $l_j{}^p l_{j-1}{}^n$ means p protons in the $j=l+\frac{1}{2}$ state, which are completely filled by neutrons, and n neutrons in the $j=l-\frac{1}{2}$ state, with the resultant spin J corresponding to the odd number. For even-A nuclei, the two subscripts in $(l_j)_{J,T}{}^N$ mean total spin and isotopic spin, respectively. If p and n are both odd, a resultant spin $J=1$ has to be assumed for allowed transitions from a $l_j{}^p l_{j-1}{}^n$ configuration to the spin $J=0$ ground state of the even-even daughter. Column 5 gives the GT matrix element squared for the applicable single-particle wave functions. Column 6 gives the corresponding quantity for the many-particle wave functions described in Column 4. Finally, Column 7 gives the unfavored factor U, that is, the ratio of the theoretical to the observed transition probability for the j-j coupling case. The values given are generally those obtained under the assumption that T is a good quantum number (always fulfilled when the protons are in $l+\frac{1}{2}$, with neutrons in the $l-\frac{1}{2}$ shell). The values for separate antisymmetrization of protons and neutrons are given in brackets, where it is appropriate.

(A) Unfavored factors for allowed β transitions, odd-A nuclei.

A	Transition	log ft	Interpretation	(Matrix elem.)^2 S.P.	j-j	U
35	$_{16}S_{19}-{}_{17}Cl_{18}$	5.0	$(d_{3/2})_{3/2}{}^3-(d_{3/2})_{1/2}{}^3$	3/5	4/25	3.0
37	$_{16}S_{21}-{}_{17}Cl_{20}{}^x$	4.3	$f_{7/2}-f_{7/2}$	9/7	9/7	7.3
					16/7[a]	15.5[a]
	$_{18}A_{19}-{}_{17}Cl_{20}$	5.1	$(d_{3/2})_{1/2}{}^5-(d_{3/2})_{3/2}{}^5$	3/5	4/25	4.1
39	$_{17}Cl_{22}-{}_{18}A_{21}{}^{xx}$	5.3	$(d_{3/2})_{3/2}{}^5-(d_{3/2})_{1/2}{}^5$	3/5	4/25	6.0
41	$_{18}A_{23}-{}_{19}K_{22}{}^x$	5.1	$(f_{7/2})_{3/2}{}^3-(f_{7/2})_{1/2}{}^3$	9/7	4/7	14
43	$_{21}Sc_{22}-{}_{20}Ca_{23}$	4.8	$(f_{7/2})_{1/2}{}^3-(f_{7/2})_{3/2}{}^3$	9/7	4/7	6.8
					(27/28)	(11.5)
45	$_{22}Ti_{23}-{}_{21}Sc_{24}$	4.6	$(f_{7/2})_{1/2}{}^5-(f_{7/2})_{3/2}{}^5$	9/7	20/189	0.8
					(9/56)	(0.95)
47	$_{20}Ca_{27}-{}_{21}Sc_{26}$	8.6	$(f_{7/2})_{7/2}{}^5-(f_{7/2})_{5/2}{}^5$	9/7	12/49	1.8×10^4
					(9/28)	(2.4×10^4)
	$_{21}Sc_{26}-{}_{22}Ti_{25}{}^x$	5.2	$(f_{7/2})_{5/2}{}^7-(f_{7/2})_{3/2}{}^7$	9/7	8/45	5.4
					(27/112)	(7.3)
49	$_{21}Sc_{28}-{}_{22}Ti_{27}$	5.7	$(f_{7/2})_{7/2}{}^9-(f_{7/2})_{5/2}{}^9$	9/7	12/49	23
					(9/28)	(30)
51	$_{24}Cr_{27}-{}_{23}V_{28}$	5.1	$(f_{7/2})_{3/2}{}^{11}-(f_{7/2})_{5/2}{}^{11}$	9/7	16/35	11
					(7/18)	(9.3)
63	$_{30}Zn_{33}-{}_{29}Cu_{34}$	5.4	$(p_{3/2})_{1/2}{}^5-(p_{3/2})_{3/2}{}^5$	5/3	4/9	21
					(5/6)	(39)
69	$_{30}Zn_{39}-{}_{31}Ga_{38}$	4.4	$p_{1/2}-p_{3/2}$	8/3		13
			$p_{3/2}{}^2p_{1/2}-p_{3/2}{}^3$		4/3	6.5
73	$_{31}Ga_{42}-{}_{32}Ge_{41}{}^{xx}$	6.0	$p_{3/2}{}^3p_{1/2}{}^2-p_{3/2}{}^4p_{1/2}$	4/3	4/3	250
75	$_{32}Ge_{43}-{}_{33}As_{42}$	5.2	$p_{3/2}{}^2p_{1/2}-p_{3/2}{}^3$	8/3	4/3	40
77	$_{32}Ge_{45}{}^m-{}_{33}As_{44}$	4.7	$p_{3/2}{}^4p_{1/2}-p_{3/2}{}^3p_{1/2}{}^2$	4/3	8/3	28
			$p_{3/2}{}^2p_{1/2}-p_{3/2}p_{1/2}{}^2$	4/3	4/3	14
	$_{33}As_{44}-{}_{34}Se_{43}$	5.8	$p_{3/2}{}^3p_{1/2}{}^2-p_{3/2}{}^3P_{1/2}$	4/3	4/3	160
			$p_{3/2}p_{1/2}{}^2-p_{3/2}{}^2p_{1/2}$	4/3	2/3	80
	$_{35}Br_{42}-{}_{34}Se_{43}$	5.4	$p_{3/2}{}^3-p_{3/2}{}^2p_{1/2}$	4/3	2/3	32
	$_{36}Kr_{41}-{}_{35}Br_{42}$	5.4	$p_{3/2}{}^4p_{1/2}-p_{3/2}{}^3p_{1/2}{}^2$	4/3	8/3	126
81	$_{34}Se_{47}-{}_{35}Br_{46}$	4.7	$p_{3/2}{}^2p_{1/2}-p_{3/2}{}^3$	8/3	4/3	13
83	$_{34}Se_{49}-{}_{35}Br_{48}$	5.1	$p_{3/2}{}^2p_{1/2}-p_{3/2}{}^3$	8/3	4/3	31
	$_{35}Br_{48}-{}_{36}Kr_{47}{}^m$	5.0	$p_{3/2}{}^3p_{1/2}{}^2-p_{3/2}{}^4p_{1/2}$	4/3	4/3	25
85	$_{35}Br_{50}-{}_{36}Kr_{49}{}^m$	5.1	$p_{3/2}{}^3p_{1/2}{}^2-p_{3/2}{}^4p_{1/2}$	4/3	4/3	32
	$_{36}Kr_{49}{}^m-{}_{37}Rb_{48}{}^x$	5.2	$p_{3/2}{}^2p_{1/2}-p_{3/2}{}^3$	8/3	4/3	40
87	$_{40}Zr_{47}-{}_{39}Y_{48}{}^m$	5.5	$(g_{9/2})_{7/2}{}^{11}-(g_{9/2})_{9/2}{}^{11}$	11/9	16/81	12
					(11/45)	(15)
89	$_{40}Zr_{49}-{}_{39}Y_{50}{}^m$	6.1	$(g_{9/2})_{7/2}{}^{11}-(g_{9/2})_{9/2}{}^{11}$	11/9	16/81	53
					(11/45)	(65)
91	$_{42}Mo_{49}{}^m-{}_{41}Nb_{50}$	5.7	$(p_{1/2})_{1/2}{}^3-(p_{1/2})_{1/2}{}^3$	1/3	1/3	28
					4/3[a]	112[a]
	$_{42}Mo_{49}-{}_{41}Nb_{50}{}^m$	4.0	$(g_{9/2})_{5/2}{}^{13}-(g_{9/2})_{7/2}{}^{13}$	11/9	8/21	2.6
					(22/45)	(3.0)
93	$_{43}Tc_{50}-{}_{42}Mo_{51}{}^x$	4.6	$g_{9/2}{}^5-g_{9/2}{}^4g_{7/2}$	20/9	16/15	8.0
95	$_{41}Nb_{54}-{}_{42}Mo_{53}{}^x$	5.1	$g_{9/2}{}^3g_{7/2}{}^4-g_{9/2}{}^4g_{7/2}{}^3$	20/9	16/45	8.0
101	$_{43}Tc_{58}-{}_{44}Ru_{57}{}^x$	4.6	$g_{9/2}{}^5g_{7/2}{}^3-g_{9/2}{}^6g_{7/2}{}^7$	20/9	16/15	8.0
121	$_{50}Sn_{71}-{}_{51}Sb_{70}$	5.0	$d_{3/2}-d_{5/2}$	12/5		45
	$_{53}I_{68}-{}_{52}Te_{69}{}^x$	5.0	$d_{5/2}-d_{3/2}$	8/5		30
123	$_{50}Sn_{73}-{}_{51}Sb_{72}{}^x$	5.3	$d_{3/2}-d_{5/2}$	12/5		90
127	$_{52}Te_{75}-{}_{53}I_{74}$	5.6	$d_{3/2}-d_{5/2}$	12/5		180
133	$_{54}Xe_{79}-{}_{55}Cs_{78}{}^x$	5.6	$d_{3/2}{}^3-d_{5/2}d_{3/2}{}^2$	12/5	6/5	90
135	$_{54}Xe_{81}-{}_{55}Cs_{80}{}^x$	5.9	$d_{3/2}{}^3-d_{5/2}d_{3/2}{}^2$	12/5	6/5	180
141	$_{60}Nd_{81}-{}_{59}Pr_{82}$	5.1	$d_{5/2}{}^2d_{3/2}{}^3-d_{5/2}d_{3/2}{}^4$	8/5	4/5	19
	$_{61}Pm_{80}-{}_{60}Nd_{81}$	>5.3	$d_{5/2}{}^3d_{3/2}{}^2-d_{5/2}{}^2d_{3/2}{}^3$	8/5	8/15	>20

TABLE I.—*Continued.*

(B) Unfavored factors for allowed β transitions, even-A nuclei.

A	Transition	log ft	Interpretation	(Matrix elem.)[2] S.P.	j-j	U
12	$_5B_7-{}_6C_6$	4.2	$p_{3/2}{}^3p_{1/2}-p_{3/2}{}^4$	8/3	16/9	5.3
38	$_{19}K_{19}-{}_{18}A_{20}{}^x$	5.0	$(d_{3/2})_{3,0}{}^6-(d_{3/2})_{2,1}{}^6$	3/5	6/25	4.5
44	$_{21}Sc_{23}-{}_{20}Ca_{24}{}^x$	5.3	$(f_{7/2})_{3,1}{}^4-(f_{7/2})_{2,0}{}^4$	9/7	24/25	36
64	$_{29}Cu_{35}-{}_{28}Ni_{36}$	4.9	$(p_{3/2})_{1,1}{}^4-(p_{3/2})_{0,2}{}^4$	5/3	12/25	7.2
					(20/9)	(34)
	$-{}_{30}Zn_{34}$	5.3	$-(p_{3/2})_{0,0}{}^4$	5/3	12/25	18
					(5/9)	(21)
66	$_{29}Cu_{37}-{}_{30}Zn_{36}$	5.3	$(p_{3/2})_{1,1}{}^4-(p_{3/2})_{0,0}{}^4$	5/3	12/25	18
					(5/9)	(21)
68	$_{31}Ga_{37}-{}_{30}Zn_{38}$	5.2	$(p_{3/2})_{1,0}{}^6-(p_{3/2})_{0,1}{}^6$	5/3	11/10	33
					(2/5)	(12)
70	$_{31}Ga_{39}-{}_{32}Ge_{38}$	5.1	$p_{3/2}{}^3p_{1/2}-p_{3/2}{}^4$	8/3	16/9	42
80	$_{35}Br_{45}-{}_{34}Se_{46}$	4.5	$p_{3/2}{}^3p_{1/2}-p_{3/2}{}^2p_{1/2}{}^2$	4/3	8/9	6.7
	$-{}_{36}Kr_{44}$	5.5	$-p_{3/2}{}^4$	8/3	16/9	134
100	$_{43}Tc_{57}-{}_{44}Ru_{56}$	4.3	$g_{9/2}{}^5g_{7/2}{}^7-g_{9/2}{}^6g_{7/2}{}^6$	20/9	8/9	3.4
104	$_{45}Rh_{59}-{}_{46}Pd_{58}$	4.7	$g_{9/2}{}^7g_{7/2}{}^7-g_{9/2}{}^8g_{7/2}{}^6$	20/9	32/27	11.3
	$_{47}Ag_{57}-{}_{46}Pd_{58}$	>5.3	$g_{9/2}{}^9g_{7/2}{}^7-g_{9/2}{}^8g_{7/2}{}^8$	16/7	32/27	>45
106	$_{44}Ru_{62}-{}_{45}Rh_{61}$	4.3	$g_{9/2}{}^6g_{7/2}{}^8-g_{9/2}{}^7g_{7/2}{}^7$	20/9	64/9	27
	$_{45}Rh_{61}-{}_{46}Pd_{60}$	5.2	$g_{9/2}{}^7g_{7/2}{}^7-g_{9/2}{}^8g_{7/2}{}^6$	20/9	32/27	36
	$_{47}Ag_{59}-{}_{46}Pd_{60}$	5.0	$g_{9/2}{}^9g_{7/2}{}^5-g_{9/2}{}^8g_{7/2}{}^6$	16/7	8/9	17
			$g_{9/2}{}^9g_{7/2}{}^7-g_{9/2}{}^8g_{7/2}{}^8$		32/27	22
108	$_{47}Ag_{61}-{}_{48}Cd_{60}$	4.6	$g_{9/2}{}^9g_{7/2}{}^7-g_{9/2}{}^{10}g_{7/2}{}^6$	20/9	40/27	11
110	$_{47}Ag_{63}-{}_{48}Cd_{62}$	5.0	$g_{9/2}{}^9g_{7/2}{}^7-g_{9/2}{}^{10}g_{7/2}{}^6$	20/9	40/27	28
112	$_{46}Pd_{66}-{}_{47}Ag_{65}$	>3.9	$g_{9/2}{}^8g_{7/2}{}^8-g_{9/2}{}^9g_{7/2}{}^7$	20/9	32/9	>6.8
	$_{49}In_{63}-{}_{48}Cd_{64}$	4.6	$g_{9/2}{}^9g_{7/2}{}^7-g_{9/2}{}^8g_{7/2}{}^8$	16/9	32/27	9.3
	$-{}_{50}Sn_{62}$	4.1	$-g_{9/2}{}^{10}g_{7/2}{}^6$	20/9	40/27	3.7
114	$_{49}In_{65}-{}_{50}Sn_{64}$	4.5	$g_{9/2}{}^9g_{7/2}{}^7-g_{9/2}{}^{10}g_{7/2}{}^6$	20/9	40/27	9.1
116	$_{49}In_{67}-{}_{50}Sn_{66}$	4.5	$g_{9/2}{}^9g_{7/2}{}^7-g_{9/2}{}^{10}g_{7/2}{}^6$	20/9	40/27	9.1
120	$_{51}Sb_{69}-{}_{50}Sn_{70}$	4.6	$(g_{7/2})_{1,3}{}^8-(g_{7/2})_0{}^8$		(56/27)	15
			$d_{5/2}d_{3/2}-d_{3/2}{}^2$	8/5	8/5	12
122	$_{53}I_{69}-{}_{52}Te_{70}$	$\geqslant$4.8	$(g_{7/2})_1{}^{10}-(g_{7/2})_0{}^{10}$		(14/9)	18
			$d_{5/2}d_{3/2}-d_{3/2}{}^2$	8/5	8/5	19
128	$_{53}I_{75}-{}_{54}Xe_{74}$	5.9	$d_{5/2}d_{3/2}-d_{3/2}{}^2$	12/5	16/15	160
	$_{55}Cs_{73}-{}_{54}Xe_{74}$	>4.8	$d_{5/2}d_{3/2}-d_{3/2}{}^2$	8/5	8/5	>19
130	$_{55}Cs_{75}-{}_{54}Xe_{76}$	5.3	$d_{5/2}d_{3/2}-d_{3/2}{}^2$	8/5	8/5	61
	$-{}_{56}Ba_{74}$	5.3	$-d_{5/2}{}^2$	12/5	16/15	92
134	$_{57}La_{77}-{}_{56}Ba_{78}$	4.8	$d_{5/2}d_{3/2}-d_{3/2}{}^2$	8/5	8/5	19
136	$_{57}La_{79}-{}_{56}Ba_{80}$	4.5	$d_{5/2}d_{3/2}{}^3-d_{3/2}{}^4$	8/5	16/5	19
140	$_{59}Pr_{81}-{}_{58}Ce_{82}$	4.3	$d_{5/2}d_{3/2}{}^3-d_{3/2}{}^4$	8/5	16/5	12

[a] These values are obtained if Fermi interaction is included.

There are also many cases where there are additives to the shell-model configurations, that is, incompletely filled shells which are not directly involved in the transitions. Examples are $f_{5/2}$ states for nucleon numbers between 28 and 38 and $h_{11/2}$ states for nucleon numbers between 64 and 76. They will not affect the matrix elements if they are accessible to one particle type only (in most cases neutrons), but if this is not the case they will give rise to configuration mixing, as will be discussed in Sec. II. In case the additives occur only for the neutrons isotopic spin will not be a good quantum number.

The complexity of the subject imposes some limitations on the scope of this investigation. The very light nuclei ($A \lesssim 30$) show great individualities and the coupling is probably intermediate between L-S and j-j character. On the other hand, there are no allowed transitions (at least none to ground states) when the neutron number N exceeds 82. The allowed transitions thus do not extend into the region of high deformability ($N>88$), where the collective degrees of freedom play a particular role.[7]

Finally, there are the cases where the spins of an odd-particle group do not couple to a resultant $J=j$ of the individual nucleons (for instance, for 11, 25, and 43 to 47 odd nucleons). These cases are not considered here, and neither are the l-forbidden transitions, for which matrix elements cannot be computed in an elementary way.

II. DISCUSSION OF UNFAVORED FACTORS

The shell-model transition probabilities are calculated from the formula

$$1/ft_{\text{calc}}=G_F{}^2M_F{}^2+G_{GT}{}^2M_{GT}{}^2, \quad (1)$$

where M_F and M_{GT} are the Fermi and Gamow-Teller matrix elements tabulated in I. For the constants we choose the values given by Winther and Kofoed-

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

Hansen.[8]

$$G_F^2 = G_{GT}^2 = 5300^{-1} \text{ second}^{-1}. \quad (2)$$

The Fermi matrix element comes into play only in very few cases. U is the ratio $ft_{\text{observed}}/ft_{\text{calculated}}$.

Tables I(A) and I(B) present the material on allowed unfavored transitions for all transitions for which a reasonable shell model interpretation can be given. The experimental data and log ft values have been taken from the recent compilation by King,[9] where also detailed literature references are given. Some additional data for nuclei in the $f_{7/2}$ shell have been taken from Nussbaum.[10]

For the odd-A nuclei the most obvious remark is that the many-particle matrix elements are in general smaller than the single-particle ones. This is particularly so for transitions within the same j^N configurations. Therefore, they reduce to some extent the gap between the favored and the unfavored transitions, but they by no means eliminate it. With the exceptions to be noted below, this factor is now only of order 10.

There is, furthermore, a definite and conspicuous correlation between the unfavored factors and the expected purity of the configurations. Transitions for which the shell-model configurations can be expected not to be disturbed too much by configuration mixing show low U values compared to neighboring ones. Examples are S^{35}, A^{37}, Zn^{69}, Mo^{91}, Tc^{101}, and Nd^{141}. On the other hand, there are two definite regions with high U values, where configuration interaction can be expected to play a major role.

The first one is the group which has to be ascribed to $p_{3/2}$ proton and $p_{1/2}$ neutron states. A conspicuous example is given by the nuclei with $A=77$. The shell-model wave-function configurations are here in obvious notation

$$_{32}Ge^m: \quad [a_1 f_{5/2}^4 + a_2 f_{5/2}^2 p_{3/2}^2 + a_3 p_{3/2}^4;\ a_4 g_{9/2}^6 p_{1/2}],$$

$$_{33}As_{44}: \quad [b_1 f_{5/2}^4 p_{3/2} + b_2 f_{5/2}^2 p_{3/2}^3;\ b_3 g_{9/2}^6 + b_4 g_{9/2}^4 p_{1/2}^2],$$

$$_{34}Se_{43}: \quad [c_1 f_{5/2}^6 + c_2 f_{5/2}^4 p_{3/2}^2 + c_3 f_{5/2}^2 p_{3/2}^4;\ c_4 g_{9/2}^4 p_{1/2}],$$

$$_{35}Br_{42}: \quad [d_1 f_{5/2}^6 p_{3/2} + d_2 f_{5/2}^4 p_{3/2}^2 + d_3 f_{5/2}^2 p_{3/2}^4;\ d_4 g_{9/2}^2 p_{1/2}^2 + d_5 g_{9/2}^4],$$

$$_{36}Kr_{41}: \quad [e_1 f_{5/2}^6 p_{3/2}^2 + e_2 f_{5/2}^4 p_{3/2}^4;\ e_3 g_{9/2}^2 p_{1/2}],$$

where the a, b, $\cdots$ are numerical coefficients. All transitions between these nuclei are allowed. It is now seen that the transitions $Ge^{77}-As^{77}$ involves the overlapping pairs $(a_1 b_1)$, $(a_2 b_2)$, and $(a_4 b_3)$; the transition $As^{77}-Se^{77}$ the partly different pairs $(b_2 c_2)$ and $(b_4 c_4)$. The situation is similar for the other transitions. Configuration mixing is thus required to explain the allowed character of these transitions. The contrast to the similar transition $_{30}Zn_{39}-{}_{31}Ga_{38}$, where such mixing is not expected to be important, is striking.

The second region of high U factors extends from $A=121$ to 135. The allowed character of these transitions can be achieved only by $d_{5/2}-d_{3/2}$ orbitals, or possibly l-forbiddenness. The $d_{5/2}$ proton configuration must in this region ($Z=50$ to 55) be mixed with $g_{7/2}$ orbits, while on the neutron side ($N=69$ to 80) there is the irregular fill-in of the $h_{11/2}$ orbits and the reappearance of holes in the $g_{7/2}$ and $d_{5/2}$ shells. These wave functions can thus be expected to be of strongly mixed character. It is again interesting to note that Nd^{141}, which has a unique shell-model assignment, exhibits a markedly lower U value.

There are, as one always finds in nuclear systematics, some curious cases. Ti^{45} has an especially small matrix element, and a U value which would classify this transition as a favored one. The transition $_{20}Ca_{27} \rightarrow {}_{21}Sc_{26}$ with log $ft=8.6$ appears to be highly forbidden. Nussbaum[10] offers as a tentative explanation the assumption that the proton-neutron interaction may produce the configuration $[d_{3/2}^2 f_{7/2}^2;\ f_{7/2}^7]$ for Ca^{47}.

Among all of the discussed transitions, there are only two for which there should be a contribution from the Fermi interaction. The U-value for $_{42}Mo_{49}^m - {}_{41}Nb_{50}$ is then on the high side, which may be due to $g_{9/2}p_{1/2}$ configuration mixing. S^{37} does not show any exceptional features.

One of the authors[11] had suggested earlier that there might be a difference between class I decays, in which the transition can be ascribed to one last nucleon (e.g., $_{16}S_{19} - {}_{17}Cl_{18}$; $d_{3/2}-d_{3/2}$) and class II decays, in which a pair is dissolved and reformed (e.g., $_{22}Ti_{23} - {}_{21}Sc_{24}$). This hypothesis is not borne out by the present investigation. There is complete symmetry in the many-body matrix elements when, in class II, holes are substituted for particles. Also the U values given here show no systematic differences.

For the even-A nuclei[12] the great majority of allowed transitions have the assignments $j^p(j-1)^n$; $J=1$ for the odd-odd nuclei. These configurations, as remarked before,[11] occur over a wider range of neutron numbers than in odd nuclei. They seem thus to be energetically favored. The matrix elements for the transition to the even-even $J=0$ daughters are of order unity or slightly larger. In accordance with this, we observe that the U values have about the same range as for odd-A transitions; however, the log ft values are systematically somewhat smaller. This empirical fact, first noted by Feenberg and Trigg,[13] thus finds a natural explanation on the basis of the shell model. In addition, we find similar behavior as for odd nuclei. Comparatively large U factors occur where configuration mixing is to be

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[12] We again leave out the very light nuclei, for which the coupling situation is not so clear. B^{12} has been included in the list, because our formula reproduces the result given previously by E. P. Wigner in his lecture notes on "Nuclear Structure and Beta Theory," Wisconsin, 1951 (unpublished).
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expected, e.g., in the region of competition between the $(p_{3/2}f_{5/2})$, $(g_{9/2}p_{1/2})$, and $(g_{7/2}d_{5/2})$ orbitals.

There remains the general question of whether there is a systematic dependence of the unfavored factors on atomic number and on the position of N and Z with respect to the closure of shells or subshells. As for the general A dependence, we are inclined to say that there is none of statistical significance. It is true that in our range of A from 35 to 141 there are some U values below 10 for light elements (S^{35}, Sc^{43}, Ti^{45}, K^{38}) while at the upper edge they are slightly larger (Nd^{141}, Pm^{141}, La^{136}, Pr^{140}). However, there are also some low values in the intermediate range (Zn^{69}, Mo^{91}, Tc^{93}, Tc^{100}, Pd^{112}, In^{112}).

The influence of shell closures, which is definitely noticeable, seems to be an indirect one. If there are only very few particles or holes outside closed shells, then generally there is much less chance for configuration mixing, and the U values become comparatively small. On the other hand, closure of subshells seems to have as large an effect as the closure of major shells. This points to configuration mixing as the major cause for the fluctuations of U values, a finding that is supported by all the evidence presented here. Of course, the regions where mixing is most likely are also the ones with partly-filled shells, and thus of high deformability, and it may be that these effects are not nearly separable. However, calculations by one of the authors,[14] by Redlich and Wigner[15] and by Suekane[16] make it unlikely that orthogonality due to the cores being deformed differently in the initial and final states can explain a major part of the differences between the favored and unfavored transitions. It seems thus that, even for the purest shell-model configurations, there remains an unfavored factor of order three for the transition probabilities in β decay. It is our guess, and at this time a guess only, that this factor may be due to the two-particle correlations, which are not incorporated in the shell-model wave functions.

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Properties of Bk^{245}†

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The radiations of 5-day electron-capturing Bk^{245} were measured with electron spectrometer, scintillation spectrometer, and alpha pulse analyzer. Conversion electrons from 250-kev and ~390-kev transitions were observed. The electromagnetic spectrum contains L and K x-rays and 250- and 380-kev gamma rays. The relative contributions to the x-ray intensities from the primary capture processes and from excited state conversions were determined by counting coincidences between the electromagnetic radiations. Bk^{245} decays primarily by electron capture ($L/K=0.33$) to a 250-kev level in Cm^{245}. The K and L conversion coefficients of the 250-kev transition are 1.76 and 0.44, respectively, indicating that the transition is $M1$. About 6% branching decay goes to a level at 630 kev. The lifetimes of the excited states are less than 2×10^{-9} sec. The intensity of alpha-particle emission is 1.05×10^{-3} per disintegration (alpha half-life 13 yr). Three alpha groups were resolved: 5.89 Mev (26%), 6.17 Mev (41%), and 6.37 Mev (33%).

I. INTRODUCTION

A BERKELIUM isotope decaying principally by electron capture with a half-life of 4.95 ± 0.1 days has been reported by Hulet, Thompson, Ghiorso, and Street[1] and assigned to mass 245. Alpha-branching decay to the extent of about 0.1% was observed. Hulet[2] subsequently assigned L and K x-rays and 68- and 245-kev photons to the decay.

Within the past year milligram quantities of Am^{243} and Cm^{244} have become available at Argonne from plutonium irradiated in the Materials Testing Reactor.[3] With these quantities it appeared feasible to prepare sufficient quantities of Bk^{245} by the $Cm^{244}(d,n)Bk^{245}$ and $Am^{243}(\alpha,2n)Bk^{245}$ reactions to obtain more information about its disintegration processes.

II. EXPERIMENTAL

A. Bombardments and Purification

The curium target (96% Cm^{244}, 2% Cm^{245}, 2% Cm^{246}) was prepared by spreading curium nitrate solution containing about 1.5 mg of curium onto an aluminum backing, evaporating the solution to dryness, and decomposing the nitrate to the oxide in a muffle furnace at 600°C. The curium was covered with a one mil aluminum foil to reduce the alpha health hazard. The back of the target was water-cooled and the covering foil was air-cooled. The curium was bombarded for about fifteen hours at 120 μa in the external deuteron

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