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Classification of Nuclear Isomers*†

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The lifetime-energy relations of Axel and Dancoff and the K/L ratios calculated by Hebb and Nelson are shown to yield spin differences ΔI which are one unit too high for long-lived electric transitions ($\Delta I \geq 3$). These transitions are also slower than expected from Weisskopf's one-particle model and have approximately the same lifetime as magnetic transitions of equal ΔI. The lifetimes of magnetic transitions agree approximately with Weisskopf's formula. If the statistical weight of the initial state is introduced into the lifetime formula, the "scatter" of the square of the matrix elements is greatly reduced for these transitions. Most long-lived isomers show $M4$ transitions, in agreement with shell theory. Some isomeric transitions which were previously assumed to show no parity change are now interpreted as $E3$. Their occurrence in the $1g_{9/2}$ shell may be explained by assuming that for the configurations $(g_{9/2})^{3,5 \text{ or } 7}$, $7/2+$ and $g_{9/2}$ states are comparable in energy. The $7/2+$ state is lower in more than half of the cases. Empirical curves of K/L ratios plotted against Z^2/E are given. They are consistently lower than the existing theoretical curves based on nonrelativistic calculations of internal conversion coefficients. Spins of metastable and ground states are assigned for a number of nuclei. For even-even nuclei the following rule is found: the first excited state usually has spin 2 and even parity. The only mixed transitions found are $M1+E2$. Sufficiently many $E3$ transitions are established to permit the conclusion that electric transitions are slower for odd-neutron nuclei than for odd-proton nuclei. This gives strong support to a one-particle model. Among electric transitions only some $E2$ transitions are faster than expected on the one-particle model. This is interpreted as a cooperative phenomenon, related to the existence of large quadrupole moments.

INTRODUCTION

AMONG nuclei of odd mass number nuclear isomers occur predominantly just before the number of protons or neutrons, whichever is odd, reaches a "magic number."[1,2] The position of these "islands," as well as the value of the magic numbers, can be most easily explained in terms of the strong spin orbit coupling model.[3,4] However, in the island which precedes magic number 50, where $g_{9/2}$ and $p_{1/2}$ levels should be adjacent and should give rise to isomeric transitions of spin change $\Delta I = 4$ with change of parity ($M4$ transitions),[5] there are two families of isomers which differ in half-life by factors of the order of 10^5 for similar energy and similar nuclear charge. Two typical examples, representative of the short-lived and the long-lived families respectively, are ${}_{47}\text{Ag}^{107m}$ ($T_{1/2} = 44$ sec, $E = 94$ kev) and ${}_{41}\text{Nb}^{91m}$ ($T_{1/2} = 60$ days, $E = 104.5$ kev). In the classification of nuclear isomers which Axel and Dancoff[6] have carried out, Nb^{91m} appeared as an isomeric transition of multipole order 5, and Ag^{107m} as one of multipole order 4. While the isomeric transition in Nb^{91m} could therefore be considered as an $M4$ transition, in agreement with shell theory, the transition in Ag^{107m} was ascribed no parity change. This is in contradiction to the strong spin-orbit coupling model, as emphasized by several authors.[3,7,8]

In the next shell, closing at magic number 82, the long-lived isomeric transitions are expected to be of the $M4$ type, according to the strong spin-orbit coupling model: $h_{11/2} \rightarrow d_{3/2}$, followed by a second step, $d_{3/2} \rightarrow s_{1/2}$ whenever the ground state is $s_{1/2}$. This is indeed found to be so, but a search for internal conversion electrons[9] or unconverted γ-rays[10] from the expected ($E5$) cross-over transitions ($h_{11/2} \rightarrow s_{1/2}$) has so far been unsuccessful. The new lifetime-energy relations recently derived by Weisskopf[11] give considerably smaller radiation probabilities for $E5$ transitions than the old ones.[12]‡ Although

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* Preliminary reports of this work were given at the American Physical Society Meeting in New York, January, 1951, M. Goldhaber, Phys. Rev. **82**, 323 (1951); and at Washington, April, 1951, A. W. Sunyar and M. Goldhaber, Phys. Rev. **83**, 216 (1951). Related work was reported at Washington by S. A. Moszkowski, Phys. Rev. **83**, 240 (1951).

† Research carried out under contract with the AEC.

[1] E. Feenberg and K. C. Hammack, Phys. Rev. **75**, 1877 (1949).

[2] L. W. Nordheim, Phys. Rev. **75**, 1894 (1949).

[3] M. G. Mayer, Phys. Rev. **78**, 16, 22 (1951).

[4] Haxel, Jensen, and Suess, Z. Physik **128**, 301 (1950).

[5] The following designations of isomeric transitions are used here:

	$E1$	$M1$	$E2$	$M2$	$E3$	$M3$	$E4$	$M4$	$E5$
$\lvert\Delta I\rvert$	1	1	2	2	3	3	4	4	5
Parity change	yes	no	no	yes	yes	no	no	yes	yes
Multipole order (Λ)	1	2		3		4		5	

[6] P. Axel and S. M. Dancoff, Phys. Rev. **76**, 892 (1949).

[7] E. Feenberg, Phys. Rev. **77**, 771 (1950).

[8] P. Axel, Phys. Rev. **80**, 104 (1950).

[9] R. D. Hill, Phys. Rev. **76**, 186 (1949); J. C. Bowe and G. Scharff-Goldhaber, Phys. Rev. **76**, 437 (1949); Katz, Hill, and Goldhaber, Phys. Rev. **79**, 781 (1950); J. W. Mihelich and R. D. Hill, Phys. Rev. **79**, 781 (1950).

[10] E. der Mateosian and M. Goldhaber, unpublished.

[11] V. F. Weisskopf and J. Blatt, privately circulated chapter from forthcoming book on *Nuclear Theory*.

[12] The lifetime-energy relations used by Axel and Dancoff for transitions of multipole order Λ are:

$$\tau_\gamma \text{ (sec)} = 3(\Lambda!)^2 \frac{1}{\rho^{2\Lambda}} \left(\frac{137}{W}\right)^{2\Lambda+1} \frac{\hbar}{mc^2},$$

where ρ is a dimensionless quantity equal to the nuclear radius $R = 1.5 \times 10^{-13} A^{\frac{1}{3}}$ cm divided by $e^2/mc^2 = 2.82 \times 10^{-13}$ cm, W = transition energy in mc^2 and $\hbar/mc^2 = 1.31 \times 10^{-21}$ sec. Weisskopf's lifetime-energy relations for electric transitions of spin change ΔI are:

$$\tau_\gamma \text{ (sec)} = \frac{\Delta I[1 \cdot 3 \cdots (2\Delta I+1)]^2}{2(\Delta I+1)} \frac{1}{\rho^{2\Delta I}} \left(\frac{137}{W}\right)^{2\Delta I+1} \frac{\hbar}{mc^2}.$$

For magnetic transitions of spin change ΔI they are: $(\tau_\gamma)_{\Delta I, \text{ magn}} = (\tau_\gamma)_{\Delta I, \text{ el}} \times (McR/\hbar)^2$, where M is the mass of a nucleon. For this goes a long way towards explaining the absence of $E5$ crossover transitions, as was pointed out by Hill,[13] the theoretical values are still larger than the experimental upper limits for these transition probabilities. On the other hand, in apparent contradiction to this fact, the "K/L ratios" obtained experimentally for some $M4$ transitions are found to lie between the theoretical values[14] for $M4$ and $E5$, and have been interpreted in the past as indicating a mixture of $M4$ and $E5$ radiations. This seemed reasonable as long as lifetime energy relations were used which were identical for $M4$ and $E5$ transitions (identical for equal multipole order Λ).

In this paper it will be shown how the above three difficulties, as well as some others, can be resolved. They are, in short:

(1) Occurrence of isomers of apparently no parity change in the $1g_{9/2}$ shell (10 cases):[15] Se^{77}, Se^{79}, Se^{81}, Kr^{79}, Kr^{81}, Kr^{83}, Rh^{103}, Rh^{105}, Ag^{107}, Ag^{109}; and in the $1h_{11/2}$ shell (3 cases): Cd^{111}, Xe^{127}, Au^{197}.
(2) Absence of $E5$ (crossover) transitions in the $1h_{11/2}$ shell.
(3) Interpretation of the experimental K/L ratios as indicating that $E5$ transitions have half-lives of the same order as $M4$ transitions of similar energy.

Two further difficulties of the previous classifications are:

(4) Absence of isomers of multipole order $\Lambda=3$, and
(5) Absence of isomers in the millisecond region.

These two difficulties were sometimes believed to be closely connected.

We have used a semi-empirical approach, using only experimental results and well-founded theoretical calculations, e.g., the relativistic internal conversion coefficients computed by Rose, Goertzel, Spinrad, Harr, and Strong.[16] We shall show that the assumption of strong spin-orbit coupling is compatible with the empirical results concerning isomers, provided we give up the rule[3] that $j-j$ coupling of an odd number of particles in the $1g_{9/2}$ shell leads always to a $g_{9/2}$ state as the configuration of lowest energy. Theoretically, this rule can only be expected to hold for zero range forces, and it is known to break down in some other shells ($1d_{5/2}$, $1f_{7/2}$), where forces of finite range can be shown to yield lowest configurations different from j, in agreement with experiment.[17]

In the course of this investigation some other results have been obtained of which the most important are:

Empirical curves of K/L ratios are given (Sec. IV) which may replace for the time being the less accurate non-relativistic theoretical curves.[14]

An empirical law connecting the lifetime of $M4$ transitions with energy, mass number of isomer and spin of the metastable state is found and compared with Weisskopf's formula for $M4$ transitions (Sec. I).

For $E3$, $E4$, and $E5$ transitions the multipole order is shown to have been previously overestimated by one unit (Secs. I and II).

Electric transitions (except some $E2$ transitions) have a slower rate than that given by Weisskopf's formula, and have half lives comparable to magnetic transitions of the same spin change (Secs. III and IV).

The only mixed transitions that occur are $M1+E2$ (Sec. III).

For even-even nuclei the first excited state has in most cases the spin $I=2$ and even parity (Sec. V).

I. $\Delta I=4$ OR 5

It is convenient to start with the long-lived isomers which contain most of the well-investigated examples. Axel and Dancoff's[6] classification contained among the isomers of $\Lambda=5$ only one example of an isomer which appeared to show an $E5$ transition: In^{114m}. Here the experimental K/L ratio[18] of 1.1 agrees well with Hebb and Nelson's[14] theoretical value for an $E5$ transition, 1.2. The experimental K conversion coefficient,[18] 2.1, does not agree with that expected for an $E5$ transition from the table of Rose *et al.*,[16] *viz.*, 12, but rather with the value computed for an $E4$ transition, 2.4. However, for an $E4$ transition, the theoretical K/L ratio[14] would be 2.6. Since the K conversion coefficients of Rose *et al.* can be considered as practically exact and the nonrelativistic K/L ratios as only approximate, we conclude that the isomeric transition in In^{114} is $E4$ rather than $E5$ and that the K/L ratios of Hebb and Nelson[14] for $E4$ transitions are too high. A further example of an $E4$ transition occurs in the first step of the isomeric transition of $Mo^{93\pm1}$ (7 hr),[19] recently investigated in more detail in this Laboratory.[20]

Two more examples of isomers tentatively identified as $E4$ transitions, Sc^{44}, and Pa^{234} (UX_2), are included in Table I, which summarizes the experimental and theoretical information on $E4$ transitions. The conversion coefficient of Sc^{44} is compatible either with an $E4$ or $M4$ transition, but an empirical rule for $M4$ transi-

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electric transitions where $\Lambda=\Delta I$ the two formulas differ only by numerical factors. The lifetimes predicted by Weisskopf's formula compared with those obtained from Axel and Dancoff's formula are larger by the following factors:

$E1$	$E2$	$E3$	$E4$	$E5$
0.75	6.25	~38	~207	~1040

‡ *Note added in proof:* Dr. J. Blatt has kindly informed us of a recent modification of Weisskopf's formulas. All lifetimes should be multiplied by $((\Delta I+3)/\Delta I)^2$ and those for the magnetic transitions by ~1/10 to take account of the effect of the intrinsic magnetic moment of the nucleons.

[13] R. D. Hill, Phys. Rev. **81**, 470 (1951).

[14] M. H. Hebb and E. Nelson, Phys. Rev. **58**, 486 (1940); N. Tralli and I. S. Lowen, Phys. Rev. **76**, 1541 (1949).

[15] Sr^{85m} should probably be added to this group, but its decay is complicated due to the existence of a K-branch. [M. Ter-Pogossian and F. Porter, Phys. Rev. **81**, 1057 (1951); Deutsch, Goldhaber, Scharff-Goldhaber, and Sunyar, unpublished.]

[16] Rose, Goertzel, Spinard, Harr, and Strong, privately circulated tables.

[17] D. Kurath, Phys. Rev. **80**, 98 (1950); I. Talmi, Phys. Rev. **82**, 101 (1951).

[18] F. Boehm and P. Preiswerk, Helv. Phys. Acta **22**, 331 (1949).

[19] Kundu, Hult, and Pool, Phys. Rev. **77**, 71 (1949).

[20] der Mateosian, Alburger, Friedlander, Goldhaber, Scharff-Goldhaber, and Sunyar, unpublished. The mass number of the Mo isomer is not yet definitely assigned.

TABLE I. Summary of information on $E4$ group of isomers.[a]

	$T_{\frac{1}{2}}$	E (kev)	Theor. K conv. coeff. α	Exp. K/L ratio	Total conv. coeff. Exp.	Total conv. coeff. Calc.	$\mathrm{Log}_{10}\tau_\gamma$	$\lvert M\rvert^2$
Sc^{44}	2.44 day	269	0.12	8	0.07	0.14	5.54	4.8×10^{-2}
$Mo^{93\pm1}$	7 hr	256	0.58	2.8	0.7	0.78	4.81	5.5×10^{-2}
In^{114} [b]	50 day	192	2.4	1.1	4	4.6	7.54	8×10^{-4}
$Pa^{234}(UX_2)$	5.7×10^4 sec[c]	394	0.3	<0.3	$\alpha_{L+M}\approx1$	~1.3	5.28	3.3×10^{-5}

[a] Values in this and the following tables for which no references are given are taken from "Nuclear Data" by K. Way *et al.*, Natl. Bur. Standards circular 499 and from the supplement 1 to this circular.

[b] Further evidence in favor of an $E4$ assignment for In^{114} has been recently given by R. M. Steffen (private communication).

[c] The partial half-life for the isomeric branch is given here.

tions, discussed below, makes it unlikely that Sc^{44} belongs to the $M4$ group. It decays ~50 times faster than expected for an $M4$ transition.

In this and the following tables, theoretical internal conversion coefficients $\alpha=N_e/N_\gamma$ are taken from the tables of Rose *et al.*[16] for $E>150$ kev. For lower energies an extrapolation suggested by Axel and Goodrich[21] is used. The ratio of the relativistic K conversion coefficients obtained from Rose *et al.* to the nonrelativistic coefficients of Hebb and Nelson[14] is plotted above $E=150$ kev and extrapolated to one at zero electron energy. K conversion coefficients below 150 kev are then obtained by multiplying Hebb and Nelson's values with a correction factor obtained from the ratio plot.

To calculate the total conversion coefficient, the K/L ratio is taken either from experiment or from empirical curves obtained from measured K/L ratios for $M4$, etc., transitions (Fig. 1 and later figures). Conversion in the M, N, etc., shells is neglected, wherever measurements are not available.

Most known long-lived isomers belong to the $M4$ group in agreement with expectations from shell theory. Table II summarizes the experimental and theoretical data on the $M4$ group of isomers. Some of the transitions take place in two successive steps. The initial and final spins of the states between which the longer lived isomeric transition takes place are indicated by I_i and I_f, respectively. Whenever a second transition takes place before the ground state (I_g) is reached, information about the second step is given. The spins and configurations tabulated are based either on existing measurements, or deductions from β-decay schemes and shell theory.

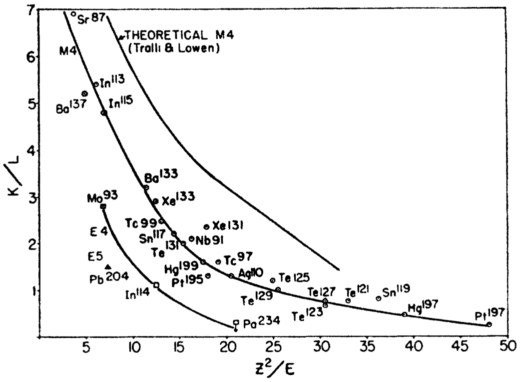

FIG. 1. Experimental K/L ratios for $M4$, $E4$, and $E5$ transitions. The nonrelativistic theoretical curve for $M4$ is shown for comparison. The theoretical curves for $E4$ and $E5$, which are not shown, are also higher than the corresponding experimental points (E in kev).

The information which exists on $E5$ transitions is rather meager. Only one such transition can be identified with certainty. It occurs in Pb^{204} and was previously believed to be an $E6$ transition. Its properties are as follows:[22] $T_{1/2}=68$ min; $E=905$ kev; $K/L=1.5\pm0.2$; ϵ (total)$\simeq$10 percent; α_5 (theoretical) = 10 percent.§ Lower limits for radiation lifetimes may be computed for two other transitions (Te^{121} and Cd^{115}) which are expected to be $E5$ transitions. The spin assignments leading to this expectation are based on investigations which do not involve the direct observation of the isomeric transition: the two-step isomeric transition[9] in Te^{121} and the β-decay of the two isomers[23] of Cd^{115}.

In Fig. 2, $\log_{10}\tau_\gamma$ (sec) is plotted *vs* $\log_{10}E$ (kev) for isomers of the $E4$, $M4$, and $E5$ group, where

$$\tau_\gamma=T_{1/2}(1+\alpha_{\mathrm{total}})/\ln 2.$$

Some points appear twice, with different internal conversion corrections made, e.g., Mn^{52}, once assuming an $E4$ correction, and once assuming an $M4$ correction. To calculate τ_γ, the experimental value of α_{total} was used wherever it agrees approximately with the theoretical value. In the few cases where there are large discrepancies and where there exists supporting evidence for assigning the isomeric transition, the theoretical value was used.

The following empirical rule follows from Fig. 2: For a given energy and a spin change $\Delta I=4$ the γ-lifetime of a transition is not appreciably affected by the fact that the parity may or may not change. This rule is contrary to previous theoretical expectations. A rough empirical formula for the γ-lifetime for $\Delta I=4$ can be deduced from Fig. 2: $\log\tau_\gamma$ (sec)$\simeq27.7-\log E$(kev).

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[21] P. Axel and R. F. Goodrich, Technical Report, University of Illinois, 1950.

[22] Sunyar, Alburger, Friedlander, Goldhaber, and Scharff-Goldhaber, Phys. Rev. **79**, 181 (1950).

§ We designate experimental conversion coefficients by ϵ and theoretical conversion coefficients for 2^l electric or magnetic transitions by α_l and β_l, respectively.

[23] The Cd^{115} isomers have been studied by R. W. Hayward and A. C. Helmholz, Phys. Rev. **75**, 1469(A) (1949) and by D. W. Engelkemeier, Argonne National Laboratory, unpublished.

TABLE II. Summary of information on $M4$ isomers.

Isomer	$T_{1/2}$	E (kev)	Theor. K conv. coeff.	K/L Ratio		Total conv. coeff.		$\mathrm{Log}_{10}\tau_\gamma$ (sec)	$\|M\|^2$	Spins		$\|M'\|^2$	Second step				Reference
				Exp.	Emp. curve	Exp.	Calc.			I_i	I_f		E (kev)	$T_{1/2}$	I_g	K/L	
Mn^{52}	1.26×10^5 sec*	390	∼0.05		>8		∼0.05	5.28	1.40	low	high				⋯†		
Zn^{69}	13.8 hr	439	0.05		∼8	0.06	∼0.06	4.88	0.685	$g_{9/2}$	$p_{1/2}$	0.455			⋯		
Kr^{85}	21.2 hr*	300	0.46		∼6.5		0.53	5.23	5:97	$p_{1/2}$	$g_{9/2}$	0.795			⋯		a
Sr^{87}	2.80 hr	394	0.23	6.9		0.29	0.27	4.27	5.25	$p_{1/2}$	$g_{9/2}$	0.63			⋯		b, c
Y^{87}	14 hr	389	0.23	8.3			∼0.27	4.97	1.05	$g_{9/2}$	$p_{1/2}$	0.63			⋯		b, c
Y^{89}	14 sec	920	0.008		>8	0.01	$\sim9\times10^{-3}$	1.31	1.67	$g_{9/2}$	$p_{1/2}$	1.11			⋯		d
Y^{91}	51 min	610	0.035		>∼7	∼0.1	$\sim4\times10^{-2}$	3.68	0.322	$g_{9/2}$	$p_{1/2}$	0.21			⋯		
Zr^{89}	4.5 min	555	0.07		∼7		$\sim8\times10^{-2}$	2.62	9.08	$p_{1/2}$	$g_{9/2}$	1.23			⋯		
Nb^{91}	60 day	104.5	∼180	2.1		100	∼270	8.90	15.3	$(p_{1/2})$	$(g_{9/2})$	2.05			⋯		e
Nb^{95}	90 hr	216	3.4		4.5	large	4.2	6.39	6.66	$p_{1/2}$	$g_{9/2}$	0.89			⋯		
Nb^{97}	60 sec	749	0.0165	≥∼4		0.015	$\sim2\times10^{-2}$	1.94	2.47	$p_{1/2}$	$g_{9/2}$	0.33			⋯		f
Tc^{95}	∼5 yr*	39	∼16,000		0.33		∼64,000	∼13.16	∼5.52	$p_{1/2}$	$g_{9/2}$	∼0.725			⋯		g
Tc^{97}	90 day	97	∼250		1.5	large	∼420	9.67	4.46	$p_{1/2}$	$g_{9/2}$	0.59			⋯		
Tc^{99}	432 hr*	142.3	31	∼2.5			46.5	8.03	6.12	$p_{1/2}$	$g_{9/2}$	0.835			⋯		h
Ag^{110}	5.4×10^8 sec*	116	∼100	∼1.3		large	∼177	∼10.98	∼0.034	(5−)	(1+)	$\sim2.5\times10^{-2}$			⋯		
In^{113}	1.73 hr	390	0.44	5.4		0.7	0.55	4.144	4.05	$p_{1/2}$	$g_{9/2}$	0.542			⋯		
In^{115}	5.11 hr*	338	0.8	4.8		0.33	0.98	4.702	3.91	$p_{1/2}$	$g_{9/2}$	0.523			⋯		
Sn^{117}	14.5 day	159	33	2.2			48	7.95	1.91	$h_{11/2}$	$d_{3/2}$	1.30	162		$s_{1/2}$		
Sn^{119}	245 day	69	∼1900	∼0.8			∼4300	11.12	2.26	$h_{11/2}$	$d_{3/2}$	1.82	24.2		$s_{1/2}$		i
Te^{121}	154 day	82	∼950	0.75		large	∼2450	10.67	1.24	$h_{11/2}$	$d_{3/2}$	1.00	213		$s_{1/2}$	7.3	j
Te^{123}	104 day	88.5	620	0.68			1740	10.35	1.32	$h_{11/2}$	$d_{3/2}$	1.06	159		$s_{1/2}$	8.6	j
Te^{125}	58 day	109	205	1.2		>100	375	9.43	1.62	$h_{11/2}$	$d_{3/2}$	1.30	35.4		$s_{1/2}$	∼7.3	
Te^{127}	90 day	88.5	620	0.75		≥5.7	1635	10.263	1.545	$h_{11/2}$	$d_{3/2}$	1.24			⋯		k
Te^{129}	33.5 day	106	245	1		∼∞ ≥1.9	490	9.34	2.46	$h_{11/2}$	$d_{3/2}$	1.95			⋯		k
Te^{131}	3.0 day*	183.2	16.5	2		≥0.6	24.7	6.98	4.10	$h_{11/2}$	$d_{3/2}$	3.32			⋯		k
Xe^{129}	8 day	196	16	$\frac{K}{L+M}$ 2.1			23.6	7.39	0.86	$h_{11/2}$	$d_{3/2}$	0.70	(39?)		$s_{1/2}$		l
Xe^{131}	12 day	163	34	2.34			53	7.91	1.33	$h_{11/2}$	$d_{3/2}$	1.06			⋯		m
Xe^{133}	2.30 day	232	6.6	2.9			9.6	6.42	1.57	$h_{11/2}$	$d_{3/2}$	1.26			⋯		n
Xe^{135}	15.3 min	520	0.22		5.5		0.26	3.22	1.78	$h_{11/2}$	$d_{3/2}$	1.43			⋯		
Ba^{133}	38.9 hr	276	3.5	3.2		2.45	4.6	6.05	0.784	$h_{11/2}$	$d_{3/2}$	0.63			⋯		
Ba^{135}	28.7 hr	300	2.3		3.5		3	5.77	0.705	$h_{11/2}$	$d_{3/2}$	0.564			⋯		
Ba^{137}	2.6 min	669	0.1	5.2		∼0.12	0.12	2.40	1.18	$h_{11/2}$	$d_{3/2}$	0.945			⋯		o
Pt^{195}	∼80 min	337	5.2	1.3		large	9.2	4.86	0.97	$i_{13/2}$	$f_{5/2}$	0.90	?		$p_{1/2}$		
Pt^{197}	3.5 day	126	170	0.23			910	8.60	1.21	$i_{13/2}$	$f_{5/2}$	1.15	?		?		
Hg^{197}	23 hr	164	85	0.45		∼4.5	360	7.65	1.00	$i_{13/2}$	$f_{5/2}$	0.937	133	7×10^{-9} sec	$p_{1/2}$	0.39	p
Hg^{199}	44 min	368	4.4	1.6		>11	7.2	4.50	0.975	$i_{13/2}$	$f_{5/2}$	0.91	158.5		$p_{1/2}$	0.37	
Pb^{207}	0.9 sec	1050	0.103		∼5.2		∼0.12	0.164	1.54	$i_{13/2}$	$f_{5/2}$	1.45	520		$p_{1/2}$		q

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[*] Partial half-life for isomeric transition is given wherever branching is known to occur.

[†] Whenever the ground state is also the final state of the first isomeric transition, this is indicated by ⋯.

[a] I. Bergström and S. Thulin, Phys. Rev. **79**, 537 (1950).

[b] L. G. Mann and P. Axel, Phys. Rev. **80**, 759 (1950) and private communication.

[c] E. K. Hyde and G. D. O'Kelley, Phys. Rev. **82**, 944 (1951).

[d] Goldhaber, der Mateosian, Scharff-Goldhaber, Sunyar, Deutsch, and Wall, Phys. Rev. **83**, 661 (1951).

[e] J. Ovadia and P. Axel, private communication.

[f] Burgus, Knight, and Prestwood, Phys. Rev. **79**, 104 (1950).

[g] H. Medicus and P. Preiswerk, Phys. Rev. **80**, 1101 (1950).

[h] Mihelich, Goldhaber, and Wilson, Phys. Rev. **82**, 972 (1951).

[i] J. W. Mihelich, private communication of K/L ratio. The second step in Sn^{119} has recently been found (Scharff-Goldhaber, der Mateosian, Goldhaber, Johnson, and McKeown, Phys. Rev. **83**, 480 (1951) and R. D. Hill, Phys. Rev., Aug. 15, 1951.

[j] R. D. Hill, Phys. Rev. **81**, 470 (1951).

[k] J. W. Mihelich and E. Church, private communication; R. R. Williams, Jr., J. Chem. Phys. **16**, 513 (1948), finds by a Szilard-Chalmers separation that approximately 40 percent of the transitions of Te^{131m} lead to the 25-min Te^{131} ground state. This he interprets as indicating ∼40 percent internal conversion for the isomeric transition. Theoretically we should expect ∼96 percent. We therefore interpret the experimental result tentatively as indicating that the isomeric branch is only ∼40 percent, the remainder being β-decay from Te^{131m} to I^{131}. *Note added in proof:* If we similarly re-interpret Williams' results for Te^{127} and Te^{129} where he finds Szilard-Chalmers yields of ∼85 percent and ∼50 percent, respectively, and use new lifetime values obtained by R. D. Hill and M. T. Piggott (Te^{127}, $113\pm5d$; Te^{129}, $38\pm2d$) we find $|M'|^2\simeq1$ for these isomers.

[l] I. Bergström, Nature **167**, 634 (1951). C. J. Borkowski and A. R. Brosi, ORNL 607, report a 39-kev transition in the decay of I^{129}. This may be also the hitherto undiscovered second step in the decay of Xe^{129m}.

[m] I. Bergström, Phys. Rev. **80**, 114 (1950).

[n] I. Bergström, Phys. Rev. **81**, 638 (1951).

[o] D. E. Alburger, private communication. J. W. Mihelich, private communication (K/L ratio).

[p] Frauenfelder, Huber, De-Shalit, and Zünti, Phys. Rev. **77**, 139 (1950).

[q] E. C. Campbell and M. Goodrich, Phys. Rev. **78**, 640(A) (1950). *Note added in proof:* An unpublished analysis of Pb^{207} levels by M. H. L. Pryce lends further support to the level assignment given here.

To compare the empirical and theoretical mean lifetimes in detail, it is convenient to multiply τ_γ by the appropriate power of ρ (e.g., ρ^6 for $M4$ transitions) and to plot the logarithm of the product *vs* log$E$. This is done for $M4$ transitions in Fig. 3, for $E4$ and $E5$ transitions together with $E3$ transitions in Fig. 9. We can define the ratio of the experimentally obtained τ_γ (exp) to the τ_γ (theor) obtained from Weisskopf's formula as $1/|M|^2$ if we take Weisskopf's squares of matrix elements as unity for comparison. The values of $|M|^2$ are given in the tables.

It is remarkable how well most points of Fig. 3 agree with the theoretical straight line. However, some points appear to be systematically lower by approximately a factor 5. This fact is illustrated more clearly by Fig. 4(a) where the distribution in $|M|^2$ is plotted indicating two

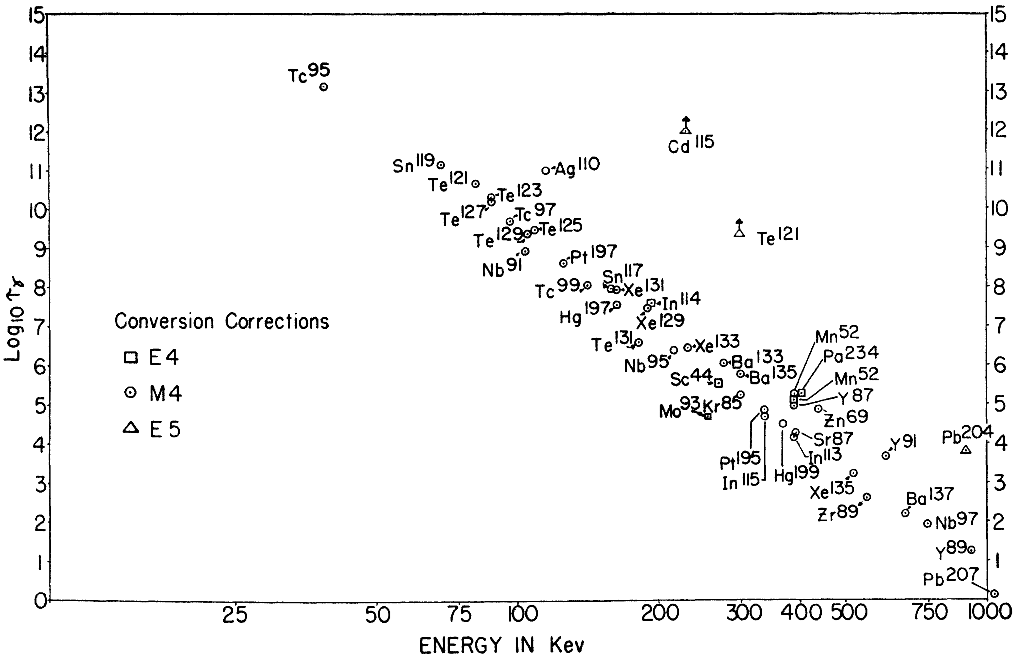

FIG. 2. Lifetime-energy relation for $E4$, $M4$, and $E5$ transitions. Mn^{52} appears twice, once with an $E4$ correction and once with $M4$ correction for internal conversion.

groups of isomers differing in $|M|^2$ by ~ 5. Especially interesting is the pair of isobars, Sr^{87m} and Y^{87m}, which have the same ρ correction, similar energy, (394 and 389 kev, respectively),[24] and a very similar internal conversion correction ($Z=38$ and 39, respectively), but half-lives of 2.80 ± 0.03 hr and 14 ± 1 hr, respectively. Thus, the half-lives are in the ratio of 1:5.[25] This is the same as the ratio of the statistical weights $(2I_i+1)$ of the initial states, *viz.* 2:10 for these two nuclei where I_i takes on the values 1/2 and 9/2, respectively.

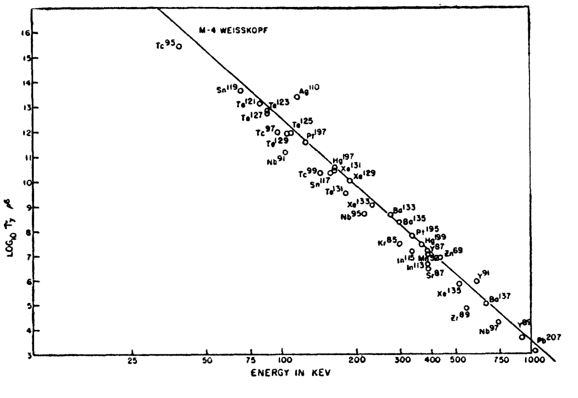

FIG. 3. Normalized lifetime-energy relation for $M4$ transitions. The theoretical relation due to Weisskopf is plotted for comparison.

Such a ratio of life times would be expected for the ideal case where the ψ-functions of the initial and final state are exactly reversed for the two isomers.[26] If we plot [Fig. 4(b)] the distribution of isomers *vs* $|M'|^2=(2I_i+1)|M|^2$, normalized at the mean value, we find that this quantity shows remarkably little deviation from the mean; it has a half-width at half-maximum of about 40 percent.

The lifetime of $M4$ transitions is given by the empirical law (see Fig. 5)

$$\tau_\gamma\ (\mathrm{sec})=1.0\times10^4(2I_i+1)/A^2E^9,$$

where $A=$ mass number, $I_i=$ spin of metastable state, and $E=$ energy in Mev. Considering that a good part of the deviation found must be due to experimental errors and approximations made in the computations, the mean deviation from the lifetime given by this formula is estimated to be <30 percent.

It is perhaps significant that the point which deviates most from the mean, Ag^{110}, where the value of $(2I_i+1)|M|^2$ is 40 times smaller than the mean, corresponds to a transition in an odd-odd nucleus, whereas all other transitions, except Mn^{52}, occur in nuclei with a single odd particle. According to shell theory, the odd particle suffers a change of three units of orbital angular momentum and a reversal of its spin in each case. The transition probabilities are approximately the same for odd-proton nuclei as for odd-neutron nuclei, with perhaps a slight tendency for larger transition probabilities

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[24] E. Hyde and G. O'Kelley, UCRL 1064; L. G. Mann and P. Axel, Phys. Rev. **80**, 750 (1950) and private communication (Mann and Axel give energies of 390 and 385 kev for Sr^{87m} and Y^{87m} respectively).

[25] A possible K capture branch in Y^{87m} has a negligible effect on the lifetime. (L. G. Mann and P. Axel, private communication.)

[26] A similar spin correction was introduced in β-decay theory by R. E. Marshak, Phys. Rev. **61**, 431 (1942).

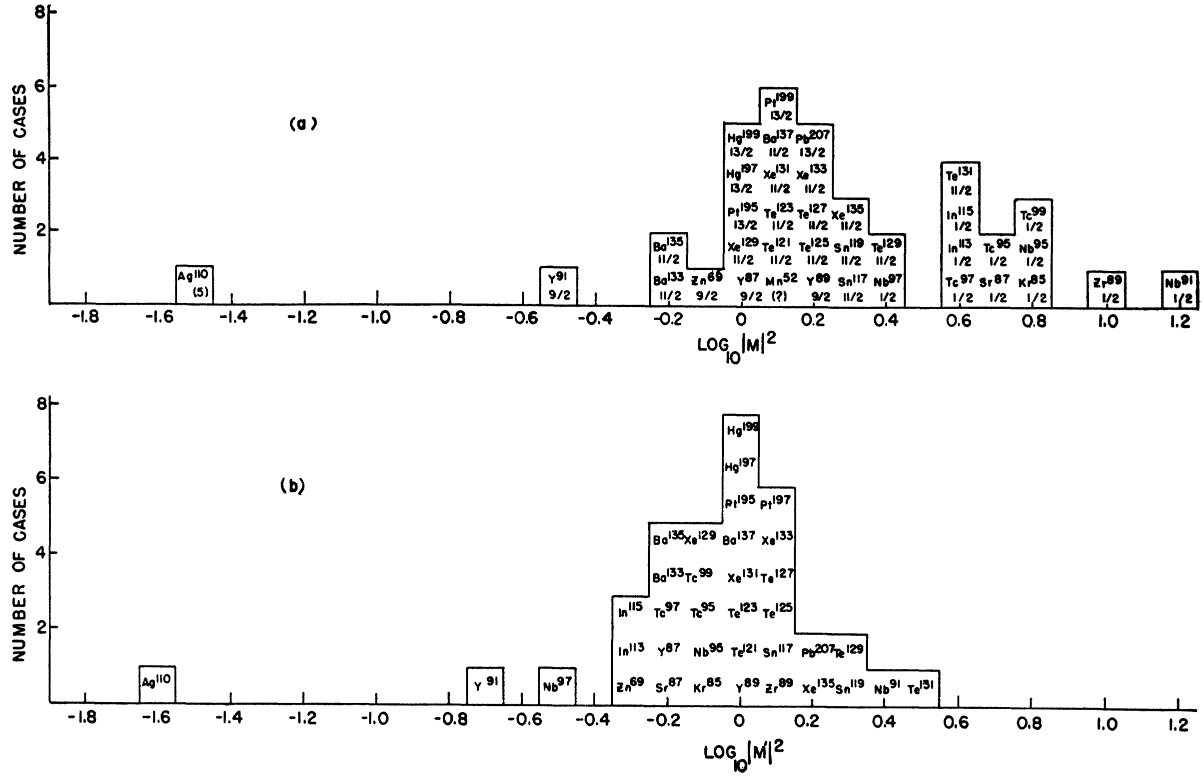

FIG. 4. Distribution of the squares of matrix elements for nuclei showing $M4$ transitions. In (a) it is plotted against $\log|M|^2$, taking Weisskopf's squares of matrix elements as unity. The spin I_i of the metastable state is indicated for each nucleus. In (b) it is plotted against the relative values of $\log[(2I_i+1)|M|^2]$, normalized at the mean value.

for odd-neutron nuclei [see Fig. 4(b)]. This tendency, if real, may also be connected with the fact that most odd-neutron nuclei shown are heavier nuclei which have $h_{11/2}\rightarrow d_{3/2}$ and $i_{13/2}\rightarrow f_{5/2}$ transitions, whereas the odd-proton nuclei shown have $g_{9/2}\leftrightarrow p_{1/2}$ transitions only. Within the $g_{9/2}\leftrightarrow p_{1/2}$ group there appears to be no distinction between odd-neutron and odd-proton nuclei.

II. $\Delta I=3$

We have seen that $E4$ and $M4$ transitions have similar lifetimes. This statement carries an important implication. The group of isomers previously identified as $M3$ and $E4$ ($\Lambda=4$) may really consist of $M3$ and $E3$ transitions. The previously "absent" $E3$ group of isomers would thus be accounted for in a very simple manner. One of the well-studied isomers of this group is Ag^{107m}. The spin and magnetic moment of the ground state are known, and it may be designated confidently as a $p_{1/2}$ level, in agreement with shell theory. For the excited state ($E=94$ kev) shell theory would predict a $g_{9/2}$ configuration and a resultant $M4$ transition, leading to a mean lifetime $\tau_\gamma=1.34\times10^{10}$ sec and a conversion coefficient, $\beta_k\approx390$; thus we should expect $T_{1/2}\approx132$ days, instead of the observed value of 44 sec. The experimental K/L ratio agrees with the theoretical one for an $E4$ transition, but we have seen above that the K/L ratios for $E4$, $E5$, and $M4$ transitions were found to be lower than the theoretical ratios. A better guide than the K/L ratio is the K conversion coefficient. Its value can be calculated from the experimental total conversion coefficient ($\epsilon=16$) and the experimental $K/(L+M)$ ratio obtained by Bradt and collaborators.[27] One finds $\epsilon_K=7.1$. In Fig. 6 we compare this value with the extrapolated values for the conversion coefficient. We see that only the $E3$ curve is close to the experimental value, indicating a $7/2+$ state[28] for Ag^{107m}.[29] Low-lying $7/2+$ states have been recently established in Tc^{99} [30,31] and Kr^{83} [32] and interpreted as due to $(g_{9/2})^{3 \text{ or } 7}$ configurations.[31] To understand the decay of Ag^{107m}, and a number of similar isomeric transitions, we would have to generalize this interpretation by saying: For the configurations $(g_{9/2})^{3,5,7}$ in the $1g_{9/2}$ shell there exist two low-lying states: $7/2+$ and $g_{9/2}$. In more than half of the cases the $7/2+$ state is lower than the $g_{9/2}$

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[27] Bradt, Gugelot, Huber, Medicus, Preiswerk, Scherrer, and Steffen, Helv. Phys. Acta **20**, 153 (1947).

[28] Following the usual convention, we designate even parity by a + sign and odd parity by a − sign.

[29] Because of conflicting reports on the properties of Ag^{109m} this isomer has been recently restudied carefully by J. Ovadia and P. Axel (University of Illinois) with results which are similar to those discussed here for Ag^{107m} (private communication).

[30] Medicus, Maeder, and Schneider, Helv. Phys. Acta **24**, 72 (1950).

[31] Mihelich, Goldhaber, and Wilson, Phys. Rev. **82**, 972 (1951).

[32] I. Bergström, Phys. Rev. **81**, 638 (1951).

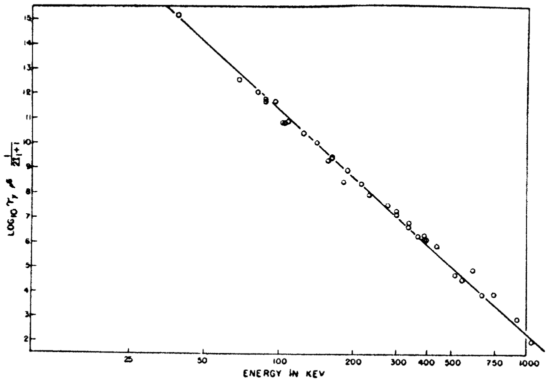

FIG. 5. Normalized lifetime-energy relations for $M4$ transitions with spin correction. The points from Fig. 3 are replotted after division by $(2I_i+1)$. The names of the isomers are left out to demonstrate the linear relation on a log scale more clearly. The line shown is fitted to the experimental points and given by the equation

$$\tau_\gamma\ (\text{sec}) = \frac{1.0\times10^4(2I_i+1)}{A^2E^9}\ (E \text{ in Mev}).$$

state. The transitions with $\Delta I=3$ in the $1h_{11/2}$ shell appear to be $E3$ for Cd^{111} [33] and Xe^{127}, but $M3$ for Au^{197}. While the $E3$ examples can be most naturally explained as $h_{11/2}\rightarrow d_{5/2}$ transitions, followed in each case by a $d_{5/2}\rightarrow s_{1/2}(E2)$ transition, the $M3$ transition in Au^{197} appears to involve a new configuration e.g., $h_{11/2}\rightarrow 5/2$—followed by more transitions.[34] The $M3$ transition in Hf^{179m} which is followed by a second step has been tentatively interpreted as $h_{9/2}\rightarrow p_{3/2}$, followed by $p_{3/2}\rightarrow p_{1/2}$.[35]

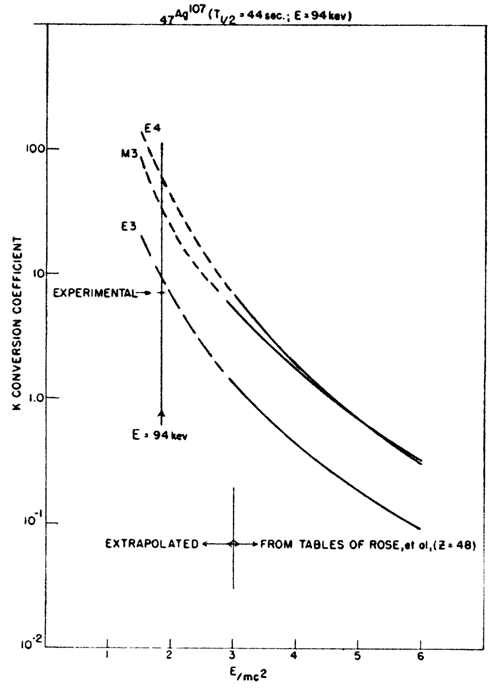

FIG. 6. Theoretical extrapolated K-conversion coefficients for Ag^{107m}. The plotted values are for the neighboring element $(Z=48)$ and would be slightly lower for $Z=47$.

In Fig. 7 the empirical K/L ratios for $E3$ transitions are compared with the theoretical ones. K/L ratios for $M3$ transitions are shown together with other magnetic transitions in Fig. 16. Table III summarizes data on $E3$ and $M3$ transitions, based in part on K/L ratios from the empirical curve. Figure 8 shows a plot of $\log\tau_\gamma$ *vs* $\log E$ for transitions with $\Delta I=3$. Again we see that the lifetime dependence is approximately the same for transitions with or without parity change. An approximate empirical formula for transitions with $\Delta I=3$ can be deduced from Fig. 8: $\log\tau_\gamma\ (\text{sec}) = 17.5-7\log E$ (kev). Figure 9 shows plots of $\log(\tau_\gamma\rho^{2\Delta I})$ *vs* $\log E$ for $E3$, $E4$, and $E5$ transitions. Experimental points and Weisskopf's theoretical lines are given. For nuclei of odd mass number, where reasonably certain spin assignments of the metastable states can be made, we have plotted the distribution of isomers *vs* $|M'|^2=(2I_i+1)|M|^2$ (relative values) in Fig. 10. It can be seen that odd proton transitions appear to be on the average faster than odd neutron transitions. $M3$ transitions are shown in Fig. 14, together with $M2$ and $M1$ transitions, on a plot of $\log(\tau_\gamma\rho^{2\Delta I-2})$ *vs* $\log E$. It is interesting to note that the three high points Br^{80m}, Hf^{179m}, and Au^{197m} probably have a high spin; a correction by the statistical weight factor would reduce the deviation from the theoretical $M3$ line.

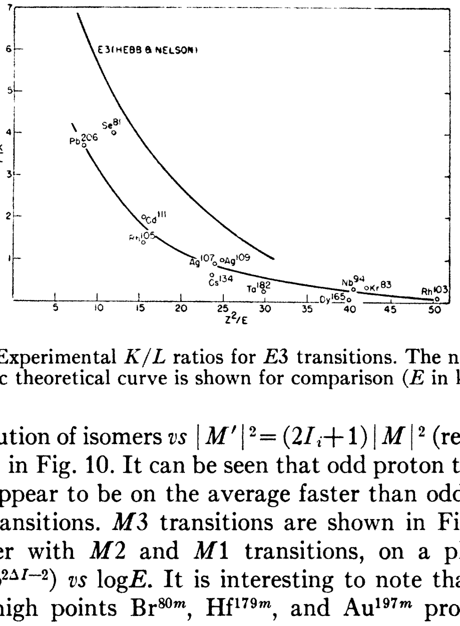

FIG. 7. Experimental K/L ratios for $E3$ transitions. The nonrelativistic theoretical curve is shown for comparison (E in kev.)

III. $\Delta I\leq 2$

For a few isomeric transitions with a spin change $\Delta I\leq 2$ the lifetime has been measured, usually by the method of delayed coincidences. K/L ratios for $E2$ transitions are shown in Fig. 11, for $M1$ and $M2$ transitions in Fig. 16. Table IV summarizes some of the

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[33] Recent work on the K conversion coefficient of the 149-kev transition in Cd^{111}, carried out in this Laboratory (A. W. Sunyar) and in Berkeley (C. L. McGinnis, private communication from A. C. Helmholz) confirms the assignment of $E3$, in agreement with the decay scheme proposed by S. Johansson, Phys. Rev. **79**, 896 (1950).

[34] Recent work at E. T. H. Zürich (private communication from D. C. Peaslee).

[35] Burson, Blair, Keller, and Wexler, Phys. Rev. **83**, 62 (1951) and E. der Mateosian and M. Goldhaber, Phys. Rev. **83**, 843 (1951).

existing data and Fig. 12 gives a plot of $\log\tau_\gamma$ *vs* $\log E$ for these transitions. A rough empirical formula for transitions with $\Delta I=2$ is $\log\tau_\gamma$ (sec) $=4-5\log E$ (kev) but the large scatter of the experimental points makes the formula of very limited practical use. Figure 13 shows a plot of $\log(\tau_\gamma\rho^4)$ *vs* $\log E$ for $E2$ transitions. Unlike the other electric transitions, some $E2$ transitions are faster than expected from Weisskopf's one particle formula. The magnetic transitions $M1$, $M2$, and $M3$ shown in Fig. 14, where $\log(\tau_\gamma\rho^{2\Delta I-2})$ is plotted *vs* $\log E$, agree fairly well with Weisskopf's formula.

IV. *K/L* RATIOS

The K/L ratios for some transitions have been shown above (Figs. 1, 7, and 11). It is useful to summarize the K/L ratios for electric and magnetic transitions (Figs. 15 and 16). One point, Hg^{196}, which can be identified as an $E1$ transition from a comparison of its observed K conversion coefficient $\epsilon_K=0.116$[36] with the theoretical $\alpha_1\cong 0.095$ from the tables of Rose *et al.*,[17] has been added to the previously discussed K/L ratios for electric transitions. The data on magnetic transitions, except $M4$, are rather sketchy. The curves $M1$-$M3$ should therefore be taken only as a rough guide to the identification of transitions. Some experimental points called $M1$ may be low due to possible admixture of $E2$ to $M1$. A case which can be identified from its experimental K conversion coefficient as a mixed transition is Tl^{203}. Here a 286-kev transition has a total conversion coefficient of 0.24 and a K/L ratio of 3.[37] Thus, $\epsilon_K=0.18$. For this energy and atomic number, the theoretical K conversion coefficients of Rose *et al.*[16] are as follows: $E2$ (7.6×10^{-2}); $M1$ (0.52). From Fig. 11, the K/L ratio expected for an $E2$ transition $(Z=81)$ would be 1.3. From this it follows that about 25 percent of the emitted quanta are $M1$ quanta and 75 percent are $E2$ quanta and that the K/L ratio for the $M1$ transition is approximately 7. The exact amount of mixing of $M1$ and $E2$ depends very sensitively on the value used for ϵ_K. A somewhat smaller value for the K/L ratio of the $M1$ transition follows from the data of Slätis and Siegbahn.[38]¶

V. FIRST EXCITED STATE OF EVEN-EVEN NUCLEI

For many nuclei where the transition from the first known excited state to the ground state has been identified, the spin and parity of the excited state can be deduced. This is particularly so for even-even nuclei which have a ground-state spin of zero and presumably even parity. The spin and parity of the first excited state then follow wherever the transition from this state to the ground state is identified from a study of one or more of the following: conversion coefficient, pair creation, lifetime, K/L ratio, angular correlation, and nuclear reactions. In Fig. 17 we show the distribution in spin and parity of the first excited state for even-even nuclei. The following rule follows: For even-even nuclei the first excited state usually has spin 2 and even parity.

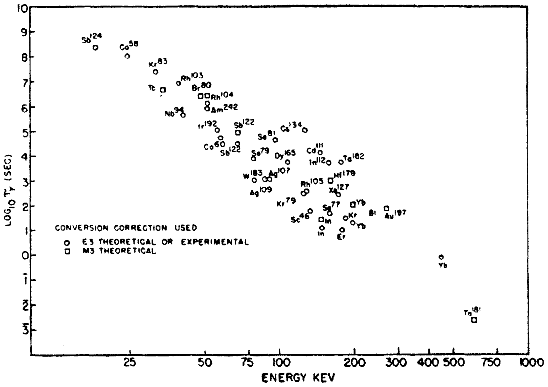

FIG. 8. Lifetime-energy relations for $E3$ and $M3$ transitions. Some points appear twice, once with an $E3$ correction and once with an $M3$ correction for internal conversion.

VI. SUMMARY AND INTERPRETATIONS

It is useful to summarize the analysis which we have given and to discuss some tentative interpretations of our results. Long-lived isomers can be divided into two classes: Those which appear systematically in islands just before the magic numbers are reached, and those which appear unrelated to magic numbers, especially among odd-odd nuclei, as well as occasionally in even-even or even-odd nuclei. Among the systematic ones there are two main groups, one of the $M4$ type,

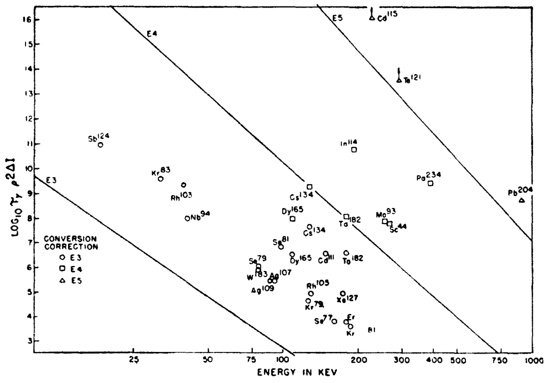

FIG. 9. Normalized lifetime-energy relations for $E3$, $E4$, and $E5$ transitions. Some points appear twice, once as $E3$ and once as $E4$, because there is at present no explicit proof existing for one or the other assignments. The theoretical lines obtained from Weisskopf's formula are shown for comparison. *Note added in proof:* A. W. Sunyar, Phys. Rev., **83**, 864 (1951), shows that Cs^{134} and Ta^{182} are $E3$ transitions. R. D. Hill, private communication, finds that the lower limit for the partial lifetime of the $E5$ crossover transition in Te^{121m} is still higher than shown here by a factor of ~20.

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[36] Steffen, Huber, and Humbel, Helv. Phys. Acta **22**, 167 (1949).

[37] D. Saxon, Phys. Rev. **74**, 849 (1948).

[38] K. Slätis and K. Siegbahn, Phys. Rev. **75**, 318 (1949) and and Arkiv. Mat. Astron. Fysik **36**, No. 21 (1949).

¶ *Note added in proof:* Dr. D. Saxon has kindly informed us that the value for ϵ_{total} quoted in Natl. Bureau Standards circular 499 is actually the value for ϵ_K. The K/L ratio for the $M1$ transition then becomes ~4.8.

TABLE III. Summary of information on *E*3 and *M*3 isomers.

Isomer	$T_{1/2}$	E (kev)	Theor. α_K	*K/L* ratio Exp.	*K/L* ratio Emp. curve	Total conv. coeff. Exp.	Total conv. coeff. Calc.	$\mathrm{Log}_{10}\tau_\gamma$	$\lvert M\rvert^2$	Spins I_i	Spins I_f	Second step E (kev)	Second step $T_{1/2}$	Second step I_g	Second step *K/L*	Reference
							*E*3 isomers									
Se^{77}	17.5 sec	162	0.74		4.5		0.9	1.68	2.36×10^{-3}	7/2+	$p_{1/2}$			···[†]		a
Se^{79}	3.9 min	80	14.5		2		21.7	3.89	1.94×10^{-3}	$p_{1/2}$	7/2+			···		b
Se^{81}	59 min	98	6	4			7.5	4.64	8.0×10^{-5}	7/2+	$p_{1/2}$			···		c
Kr^{79}	55 sec	127	2.1		3.3		2.7	2.47	1.96×10^{-3}	$p_{1/2}$	7/2+			···		
Kr^{81}	13 sec	187	0.42		4.6		0.5	1.45	1.37×10^{-3}	$p_{1/2}$	7/2+			···		
Kr^{83}	114 min	32.2	$\sim$650	$\frac{K}{L+M}$ 0.35			$\sim$2500	$\sim$7.39	3.27×10^{-4}	$p_{1/2}$	7/2+	9		$g_{9/2}$		d
Nb^{94}	6.6 min	41.5	$\sim$200	0.31			$\sim$850	$\sim$5.68	2.2×10^{-3}							e
Tc^{99}	6 hr	2.0								$p_{1/2}$	7/2+	140.3	$<10^{-6}$ sec	$g_{9/2}$	7.3	f
Rh^{103}	57 min	40	$\sim$165	$\sim$0.1			$\sim$1800	$\sim$6.95	1.29×10^{-4}	7/2+	$p_{1/2}$			···		g
Rh^{105}	45 sec	130	2.6	1.4			4.5	2.55	8×10^{-4}	(7/2)+	($p_{1/2}$)					h
Ag^{107}	44 sec	93.9	9.2	0.92		16±3	20.8	3.03	2.36×10^{-3}	7/2+	$p_{1/2}$			···		
Ag^{109}	39 sec	89	11	1.0		19±3	23.8	3.04	3.39×10^{-3}	7/2+	$p_{1/2}$			···		
Cd^{111}	48.6 min	149	1.4	2.0		2.25	2.1	4.12	7.2×10^{-6}	$h_{11/2}$	$d_{5/2}$	247	8×10^{-8} sec	$s_{1/2}$	5.12	i
Sb^{124}	21 min	18.5					α_L: 1.34×10^5	$\sim$8.39	7.06×10^{-4}	0−	3+					
Xe^{127}	75 sec	175	0.85		1.6		1.4	2.41	9.48×10^{-5}	$h_{11/2}$	$d_{5/2}$	96(125)		$s_{1/2}$		j
Cs^{134}	3.15 hr	128	2.5	0.64		5.6	6.4	5.08	1.59×10^{-6}	low	high					i
Dy^{165}	1.2 min	109	$\sim$3.5	0.076			$\sim$50	3.72	7.55×10^{-5}	$i_{13/2}$	$f_{7/2}$					e
Er	2.5 sec	180	0.75		$\sim$0.8		$\sim$1.75	0.99	1.19×10^{-3}							i
Ta^{182}	16 min	180	0.69	0.25		4.0	2.8	3.72	1.85×10^{-6}	low	high					
W^{183}	5.5 sec	80	$\sim$2	small			$\alpha_L\simeq128$	$\sim$3.02	2.71×10^{-3}	7/2+	$p_{1/2}$					
							*M*3 isomers									
Br^{80}	4.4 hr	49	$\sim$100	5.3		>57	$\sim$120	$\sim$6.45	$\sim1.55\times10^{-1}$	4 or 5	1 or 2	37			6.8	k
Tc	51.5 min	34.4	$\sim$530	1.2			$\sim$970	$\sim$6.64	$\sim$1.0							l
Hf^{179}	19 sec	161	21	$\sim$2		>19	$\sim$32	$\sim$2.95	$\sim2.8\times10^{-2}$	$h_{9/2}$	$p_{3/2}$	215	$<3\times10^{-7}$ sec	$p_{1/2}$		m
Ta^{181}	1.22×10^3 sec[*]	610	0.24		high		$\sim$0.3	$\bar{3}.36$	1.41	1/2+	$g_{7/2}$			···		n
Au^{197}	7.5 sec	273	4.2	3.4			5.5	$\bar{1}.85$	1.0×10^{-2}	$h_{11/2}$	5/2−	191		$d_{3/2}$		o
							*E*3 or *M*3 isomers									
Sc^{46}	20 sec	135	*E*3 0.66 *M*3 0.42		*E*3 >6 *M*3 high	$\sim$1	*E*3 $\sim$0.7 M3 $\sim$0.47	1.76								p
Co^{58}	8.8 hr	24.9	*E*3 $\sim$1500	1.9			*E*3 $\sim$2300	*E*3 $\sim$8.02		5±	2+					q
Co^{60}	$\sim$11 min	59	*E*3 $\sim$50	4.55			*E*3 $\sim$60	*E*3 $\sim$4.76		2+	5±					e, r
Rh^{104}	4.7 min	52	*E*3 $\sim$75 *M*3 $\sim$450		*E*3 $\sim$0.25 *M*3 $\sim$1.7	$\sim$0.65	*E*3 $\sim$375 *M*3 $\sim$715	*E*3 $\sim$6.18 *M*3 $\sim$6.47								p
In	2.5 sec	150	*E*3 1.35 *M*3 5.2		*E*3 1.8 *M*3 $\sim$5		*E*3 2.1 *M*3 $\sim$6	*E*3 1.05 *M*3 $\sim$1.40								s
In^{112}	23 min	160	*E*3 1.05 *M*3 4.5		*E*3 1.9 *M*3 $\sim$5		*E*3 1.6 *M*3 $\sim$5.5	*E*3 3.71 *M*3 $\sim$4.11								
Sb^{122}	3.5 min	69	*E*3 $\sim$24 *M*3 $\sim$200		*E*3 $\sim$0.3 *M*3 $\sim$1.8		*E*3 $\sim$104 *M*3 $\sim$310	*E*3 $\sim$4.50 *M*3 $\sim$4.99								p
Yb	6 sec	$\sim$200	*E*3 0.55 *M*3 $\sim$8		*E*3 $\sim$0.85 *M*3 $\sim$3		*E*3 $\sim$1.2 *M*3 $\sim$10.5	*E*3 $\sim$1.28 *M*3 $\sim$2.0								
Yb	0.5 sec	450	*E*3 0.046		*E*3 3		*E*3 0.06	*E*3 $\bar{1}.88$								s
Ir^{192}	1.5 min	57					*E*3 $\alpha_L\sim890$	*E*3 $\sim$5.06								
Am^{242}	80 hr[*]	52				$\sim$1		5.92								t

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[*] Partial half-life for isomeric transition is given wherever branching is known to occur.

[†] Whenever the ground state is the final state of the first isomeric transition, this is indicated by ···.

[a] W. C. Rutledge and S. B. Burson, private communication. A. C. G. Mitchell, private communication.

[b] A. Flammersfeld and W. Herr, Z. Naturforsch. **5a**, 569 (1950).

[c] The values given by I. Bergström and S. Thulin, Phys. Rev. **76**, 1718 (1949), make the value for $\lvert M\rvert^2$ somewhat smaller.

[d] I. Bergström, Phys. Rev. **81**, 638 (1951).

[e] R. L. Caldwell, Phys. Rev. **78**, 407 (1950).

[f] Mihelich, Goldhaber, and Wilson, Phys. Rev. **82**, 972 (1951).

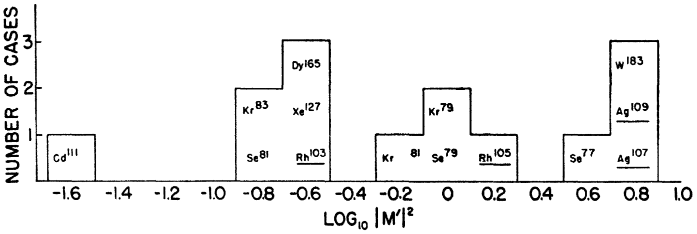
[g] Sauer, Axel, Mann, and Ovadia, Phys. Rev. **79**, 237(A) (1950), and private communication.

[h] R. B. Duffield and L. M. Langer, Phys. Rev. **81**, 203 (1951).

[i] A. W. Sunyar, Phys. Rev. **83**, 864 (1951).

Footnotes continued on following page

FIG. 10. Distribution of the squares of matrix elements for nuclei of odd mass number which show $E3$ transitions. They are plotted against the relative values of $|M'|^2=(2I_i+1)|M|^2$. Nuclei with an odd proton are underlined.



another of the $E3$ type. The first group fits the strong spin orbit coupling model: $g_{9/2}\leftrightarrow p_{1/2}$ transitions below magic number 50, $h_{11/2}\rightarrow d_{3/2}$ transitions below magic number 82, $i_{13/2}\rightarrow f_{5/2}$ transitions below magic number 126. The $h_{11/2}\rightarrow d_{3/2}$ transitions are followed by $M1$ transitions wherever the ground state is known to be $s_{1/2}$ (with Xe^{129} still insufficiently investigated). The $i_{13/2}\rightarrow f_{5/2}$ transitions are followed by $E2$ transitions wherever the ground state is known to be $p_{1/2}$ (with $Pt^{195,197}$ still insufficiently investigated). The $M4$ transitions follow an empirical law: $\tau_\gamma=C(2I_i+1)/A^2E^9$.‖ This formula is equivalent to Weisskopf's formula if the statistical weight factor $(2I_i+1)$ is introduced. The energy dependence is definitely E^9 rather than E^{11}. The most remarkable fact appears to be the small amount of "scatter" found in the experimental points, indicating a mean deviation of the squares of the matrix elements which does not exceed 30 percent. One cannot take this lack of scatter in itself as evidence for the one-particle radiation model. If that model were true in its extreme form, one would expect lower radiation probabilities for odd-neutron nuclei than for odd-proton nuclei.[39] This is not found to be so for magnetic transitions. For electric transitions, however (Fig. 10), there is a strong indication that odd-neutron nuclei have indeed lower radiation probabilities than odd-proton nuclei, thus supporting the one-particle model in a very direct way. It may be that magnetic transition probabilities are determined largely by "interaction effects"[40] which involve an average over many nucleons and are essentially the same for odd-neutron and odd-proton nuclei. The reduction in the square of the matrix element for the odd-odd nucleus, Ag^{110}, may speak for the existence of a two-nucleon jump here.

The $E3$ group of "systematically" occurring isomers contains two kinds: one for which $j-j$ coupling can account without any new assumption, showing $h_{11/2}\rightarrow d_{5/2}$ transitions, and one occurring in the $1g_{9/2}$ shell and implying the existence of a low-lying $7/2+$ state. In most of these cases the $7/2+$ state is the metastable state. In two cases where it corresponds to the ground state of long-lived radioactive nuclei, Se^{79} and Kr^{81} (see Table III), it may be possible to check the predicted spin of 7/2 experimentally. The existence of a low-lying state of spin 7/2 and even parity would be in contradiction to the strong spin orbit coupling if it were interpreted as a $g_{7/2}$ level. This level should be 1–2 Mev higher than the $g_{9/2}$ level, as the change in the binding energy at magic number 50 indicates.[41] It is therefore plausible to interpret the occurrence of a low-lying $7/2+$ level as due to a breakdown of the rule that $j-j$ coupling of a number of odd nucleons of equal j leads to a spin j as the lowest state. This rule is known to break down for Na^{23} and Mn^{55} where the configurations $(d_{5/2})^3$ and $(f_{7/2})^5$ have lowest states of spin 3/2 and 5/2 respectively. If the finite range of forces is taken into account, $j-j$ coupling is found to be compatible in these cases with the experi-

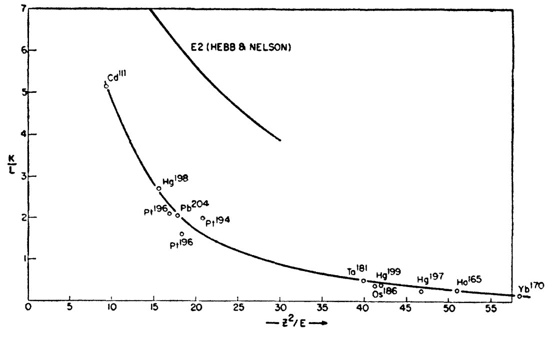


FIG. 11. Experimental K/L ratios for $E2$ transitions. The nonrelativistic theoretical curve is shown for comparison. (E in kev.)

‖ It would seem better to use three different constants for the three different families ($g_{9/2}\leftrightarrow p_{1/2}$, $h_{11/2}\rightarrow d_{3/2}$, $i_{13/2}\rightarrow f_{5/2}$). However, empirically these constants are found to be nearly equal. Had we used the equivalent formula $\tau_\gamma=c/(2I_f+1)A^2E^9$ the three empirical constants would differ considerably.

[39] In a one particle model the orbital motion of a neutron contributes to the radiation probability only indirectly through the recoil of the charged core. For electric transitions the rate is reduced by a factor $\sim(Z/A^{\Delta I})^2$. The transition probability thus becomes negligibly small for large spin changes when compared to that for nuclei with an odd proton. In spite of the contribution from the intrinsic magnetic moment of the neutron one should expect on this model a small reduction in the transition probability for magnetic transitions in odd-neutron nuclei compared with odd-proton nuclei.

[40] N. Austern and R. G. Sachs, Phys. Rev. **81**, 710 (1951).

[41] J. A. Harvey, Phys. Rev. **81**, 353 (1951).

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[j] Creutz, Delsasso, Sutton, White, and Barkas, Phys. Rev. **58**, 481 (1940). These authors find two γ-rays, 175 and 125 kev. For the second one they find only a single electron line, interpreted as a K-line. We prefer to interpret this line tentatively as an L-line of a 96-kev γ-ray, because our empirical K/L ratios would indicate that the L-line of a 125-kev $E2$ transition should be sufficiently intense to be visible.

[k] Lidofsky, Macklin, and Wu, Phys. Rev. **78**, 318(A) (1950).

[l] Medicus, Preiswerk, and Scherrer, Helv. Phys. Acta **23**, 299 (1950).

[m] E. der Mateosian and M. Goldhaber, Phys. Rev. **83**, 843 (1951). S. B. Burson, private communication.

[n] Burson, Blair, Keller, and Wexler, Phys. Rev. **83**, 62 (1951), and private communication. J. L. Wolfson (Chalk River) unpublished.

[o] Frauenfelder, Huber, De-Shalit, and Zünti, Phys. Rev. **79**, 1029 (1950).

[p] E. der Mateosian and M. Goldhaber, Phys. Rev. **82**, 115 (1951).

[q] K. Strauch, Phys. Rev. **79**, 487 (1950).

[r] Spin assignments are those given by M. Deutsch and G. Scharff-Goldhaber, Phys. Rev. **83**, 1059 (1951).

[s] E. C. Campbell, private communication.

[t] O'Kelley, Barton, Crane, and Perlman, Phys. Rev. **80**, 293 (1950).

TABLE IV. Summary of information on short-lived isomers: $M1$, $E2$, and $M2$.

Isomer	$T_{1/2}$ (sec)	E (kev)	K/L ratio Exp.	K/L ratio Emp. curve	K conv. coeff. Exp.	K conv. coeff. Calc.	Total conv. coeff. Exp.	Total conv. coeff. Calc.	Type	$\log_{10}\tau_\gamma$	$\|M\|^2$	Spins I_i	Spins I_g	Reference
Li^7	0.75×10^{-13}	478							$M1$	13.03	15.9	$p_{3/2}$	$p_{1/2}$	a
Fe^{57}	1.1×10^{-7}	14		high		~14		~16	($M1$)	$\sim\bar{6}.43$	0.025			
Cd^{111}	8×10^{-8}	247	5.12			0.053	0.06	0.06	$E2$	$\bar{7}.09$	3.2×10^{-2}	$d_{5/2}$	$s_{1/2}$	b
Eu^{153}	3×10^{-9}	70	1.3						$M1+E2$					c, d
Er^{166}	1.7×10^{-9}	80					$\alpha_L\simeq0.4$		$E2$	$\bar{8}.09$	55	2+	0+	e
Tm^{171}	2.5×10^{-6}	113					1.3							
Yb^{170}	1.6×10^{-9}	84	0.14		0.4		4.0		$E2$	$\bar{8}.06$	43	2+	0+	f
Lu^{177}	1.3×10^{-7}	150	3			6.6		8.8	$M2$	$\bar{6}.27$	25			g
Ta^{181}	2.2×10^{-5}	134	0.5			0.48		1.44	$E2$	$\bar{5}.89$	5.6×10^{-4}	1/2+	3/2+	g
Ta^{181}	$\frac{1.1\times10^{-8}}{1/9}$	345		~2.6		0.03		~0.042	$E2$	$\bar{7}.18$	2.6×10^{-3}	3/2+	7/2+	h
Ta^{181}	$\frac{1.1\times10^{-8}}{8/9}$	481	3–5	~4.3		0.017	~0.02	~0.021	$E2$	$\bar{8}.26$	4×10^{-3}	3/2+	$g_{7/2}$	h
Re^{187}	5.5×10^{-7}	133	5			~13.5		~16	$M2$	$\bar{5}.13$	5.7		$d_{5/2}$	g, i
Os^{186}	8×10^{-10}	137	0.6			~0.44	~1		$E2$	$\bar{9}.37$	16	2+	0+	j
Ir^{191}	5.7×10^{-9}	65											$d_{3/2}$	k
Hg^{197}	7×10^{-9}	133	$\frac{K}{L+M+N}$ 0.29			~0.45	~2.4	~2	$E2$	$\bar{8}.53$	1.25	$f_{5/2}$	$p_{1/2}$	l
Pb^{204}	3×10^{-7}	374	2			0.04	~0.05	0.06	$E2$	$\bar{7}.66$	5×10^{-4}	2+	0+	

[a] R. E. Bell and L. G. Elliot, Phys. Rev. **76**, 168 (1949).

[b] C. L. McGinnis, Phys. Rev. **80**, 842 (1950).

[c] F. K. McGowan, Phys. Rev. **80**, 482 (1950).

[d] J. W. Mihelich, private communication.

[e] F. K. McGowan, Phys. Rev. **80**, 923 (1950). K. Siegbahn and H. Slätis, Arkiv. Physik 1, 559 (1950).

[f] R. E. Bell and R. L. Graham, Phys. Rev. **78**, 490 (1950).

[g] F. K. McGowan, ORNL 952, 104.

[h] A. Hedgran and S. Thulin, Phys. Rev. **81**, 1072 (1951).

[i] *Note added in proof:* F. K. McGowan (private communication), has measured the conversion coefficient and finds it smaller than expected for an $M2$ transition. This may thus be an ($M1+E2$) transition.

[j] F. K. McGowan, Phys. Rev. **81**, 1066 (1951). F. R. Metzger and R. D. Hill, Phys. Rev. **81**, 300(A) (1951).

[k] F. K. McGowan, Phys. Rev. **79**, 404 (1950).

[l] F. K. McGowan, Phys. Rev. **77**, 138 (1950). M. Deutsch and W. Wright, Phys. Rev. **77**, 139 (1950). Frauenfelder, Huber, De-Shalit, and Zünti, Phys. Rev. **79**, 1029 (1950).

mental results.[17] The lowest states of the $(g_{9/2})^{3,5,7}$ configurations have not yet been calculated for forces of finite range. If we accept the interpretation that these configurations contain low-lying 7/2+ states, one of the main objections to the strong spin orbit coupling model is removed. On this interpretation no low-lying state of spin 7/2 should occur for either a single particle or a single hole in the $g_{9/2}$ shell. All isomeric transitions observed at the beginning or end of the shell are indeed of the $M4$ type. Where isomers exist, but no isomeric transition has been observed because of β-decay competition (as in $Se_{49}{}^{83}$) we can use these considerations together with evidence from the β-decay schemes to assign spins to the excited and ground states ($p_{1/2}$ and $g_{9/2}$, respectively, for the Se^{83} isomers).

The "unsystematically" occurring isomers do not appear to favor any particular spin or parity change, except that their number appears to drop off as ΔI increases, as might be expected.

Electric transition probabilities are usually considerably smaller than predicted by Weisskopf's one particle formula and their matrix elements scatter considerably. Such a behavior appears quite reasonable, as any deviation from one particle wave functions should lead, as a rule, to a reduction of the transition probability by an amount which will vary from nucleus to nucleus. The

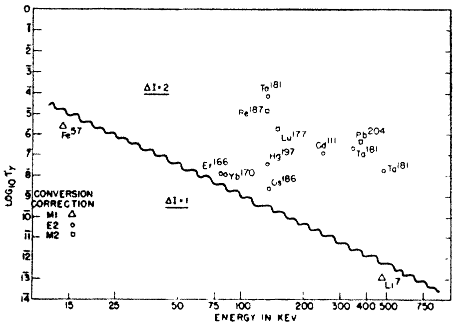

FIG. 12. Lifetime-energy relations for $E2$, $M2$, and $M1$ transitions. [The □ for Pb^{204} should be ○.]

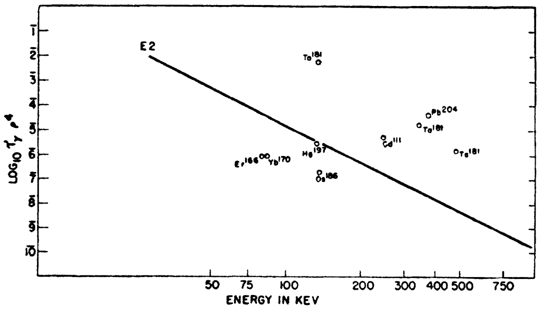

FIG. 13. Normalized lifetime-energy relation for $E2$ transitions. The theoretical line from Weisskopf's formula is shown for comparison. The existence of transitions faster than expected from the one particle model is noteworthy.

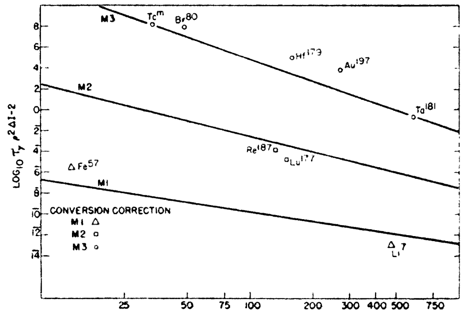

FIG. 14. Normalized lifetime-energy relations for $M1$, $M2$, and $M3$ transitions. The theoretical lines from Weisskopf's formula are shown for comparison.

tendency of odd-neutron nuclei to have lower electric transition probabilities than odd-proton nuclei may become a measure of the "purity" of the one particle wave functions: The more nearly the wave functions are represented by one particle wave functions, the shorter should be the lifetime for the case of an odd-proton nucleus and the longer for that of an odd-neutron nucleus; e.g., ${}_{47}Ag^{107}$ has an $E3$ transition of 44-sec half-life with an energy of 94 kev, whereas $Cd_{63}{}^{111}$ has one of 48.6-min half-life in spite of its considerably higher energy of 149 kev. The large fluctuations of the squares of the matrix elements which are found for electric transitions do not permit any precise predictions for the relative probabilities of transitions which can take place competitively from an excited state to two different lower states whenever one or both are electric transitions. The capricious behavior of such ratios has often been noticed, e.g., in studies of cross-over transitions of the $E4$ type competing with $E2$ transitions.

Some $E2$ transitions have squares of matrix elements >1; these are unique among the electric transitions considered here. It is conceivable that we are dealing here with a radiation analog of the "cooperative" phenomenon which is believed[42] to be responsible for the large

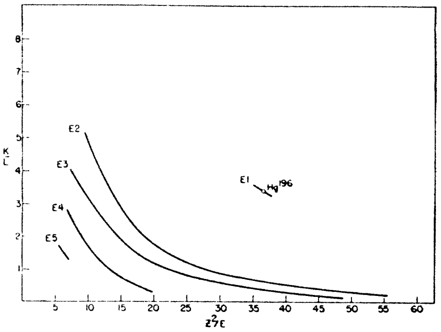

FIG. 15. Summary of empirical K/L ratios for electric transitions. For both $E5$ (see Fig. 1) and $E1$ only one point is known. For $E2$, $E3$, and $E4$ many points are known (see Figs. 1, 7, and 11). (E in kev.)

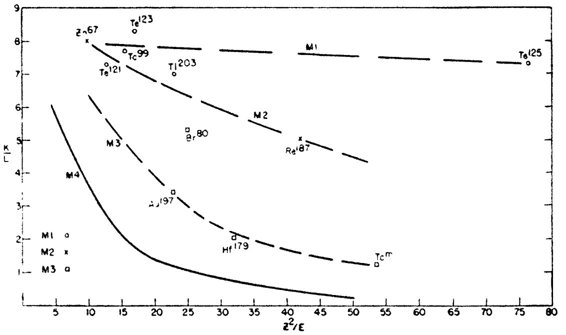

FIG. 16. Summary of empirical K/L ratios for magnetic transitions. Many points are known for $M4$ (see Fig. 1) but few are known for the other transitions where the curves must be considered as preliminary. (E in kev.) *Note added in proof:* Later work on Au^{197m} [Huber, Humbel, Schneider, de Shalit, and Zunti, Helv. Phys. Acta **24**, 127 (1951)] and Hf^{179m} [S. B. Burson and H. B. Keller, private communication] indicates that the K/L ratios for these points are higher than plotted.

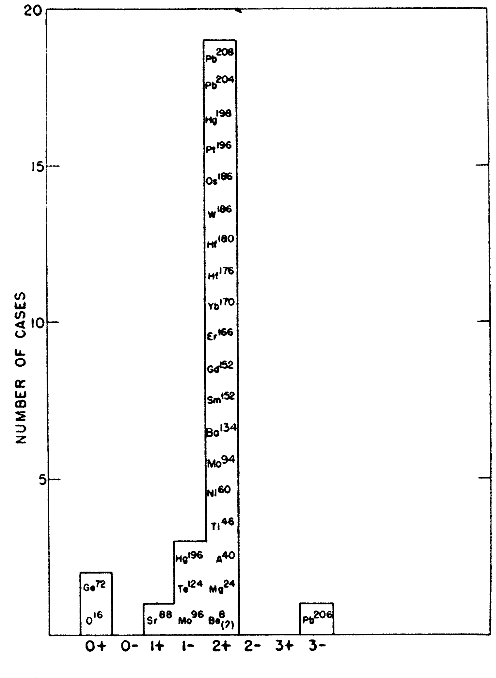

FIG. 17. Spin and parity of first excited state of even-even nuclei. The assignments given here are based in part on data given in Tables III and IV and Figs. 7, 11, and 15, as well as on the review article of Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. **22**, 291 (1950) and on "Nuclear Data" (including Supplement 1) by K. Way *et al.* (1950 and 1951). The following cases are based on more recent publications and unpublished data: Te^{124} [Langer, Moffat, and Price, Jr., Phys. Rev. **79**, 808 (1950)]; A^{40} [P. Morrison, Phys. Rev. **82**, 209 (1951)]; Sm^{152} and Gd^{152} (J. W. Mihelich, to be published); Er^{166} and Hf^{176} (Scharff-Goldhaber, Mihelich and der Mateosian, to be published); Hf^{180} (R. A. Becker, University of Illinois, private communication); W^{186} and Os^{186} [F. R. Metzger and R. D. Hill, Phys. Rev. **81**, 300(A) (1951)]; Pb^{208} (Recent results on angular correlation, obtained by H. E. Petch and M. W. Johns, Phys. Rev. **80**, 478 (1951) favor the assignment 2+ for the first excited state, in contradiction with results on internal conversion obtained by D. G. E. Martin and H. O. W. Richardson, Proc. Phys. Soc. (London) **A63**, 223 (1950) which favor 1+.)

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[42] J. Rainwater, Phys. Rev. **79**, 432 (1950). A. Bohr, Phys. Rev. **81**, 134 (1951).

static electric quadrupole moments of some nuclear ground states. The existence in the rare earth region of low lying excited states in even-even nuclei with spin 2 and even parity, from which transitions with values of $|M|^2 > 1$ take place, and the easy deformation of the core which leads to large quadrupole moments in this region may in fact be related phenomena. One should expect the one-particle model to break down for nuclei of odd mass number as soon as the excitation energy suffices to excite their even-even core. This will occur at fairly low energies in the rare earth region and may be responsible for the high level density known to exist in this region.

Because of the empirical rule that the lifetime of a γ-ray transition depends mainly on the spin change and not on the parity change, we can usually not expect an appreciable admixture of electric $(\Delta I + 1)$ radiation to magnetic ΔI radiation. The only exceptions are the $M1+E2$ transitions. The existence of such a mixed transition was first established in angular correlation studies of Y^{88}.[43] A further example, deduced from internal conversion studies, was discussed above (Tl^{203}). There can be two reasons for the occurrence of these mixtures: Selection rules may make the $M1$ transition forbidden,[40] or the $E2$ transitions may be of the "co-operative" type which can compete with $M1$ transitions. We have seen above that in the Te isomers the $d_{3/2} \rightarrow s_{1/2}$ transitions consist of $M1$ radiations with little, if any, admixture of $E2$ radiations. The lifetimes of these transitions are known to be $\lesssim 10^{-9}$ sec. If $d_{3/2}$ and $s_{1/2}$ represent pure configurations, this would indicate the existence of large interaction magnetic moments, according to the $M1$ selection rules of Austern and Sachs.[40]

The empirical lifetime-energy relations allow us to predict the energy regions where millisecond activities might be expected to occur. For $\Delta I = 2$ we should expect such activities for $E \sim 50$ kev and for $\Delta I = 3$ for $E \sim 800$ kev. They cannot, therefore, be expected to be very common and the fact that they so far have escaped detection need not be entirely due to experimental difficulties. A possible example of a millisecond transition may be the 803-kev γ-ray in Pb^{206} [44] which can be identified as an $E3$ transition from its K/L ratio (see Fig. 7).

The empirically found K/L ratios can be approximately represented as functions of Z^2/E. It is very likely that the exact K/L ratios depend in a more complicated manner on Z and E. Deviations are noticeable: low Z points are sometimes higher and high Z points lower than the average empirical curve. Such a trend may be compatible with the deviation of the empirical curve from the calculated nonrelativistic curves. The nonrelativistic curves may be expected to agree better with experiment for lower Z values, but better data are needed before a definite conclusion can be drawn.

The rule that the first excited state of an even-even nucleus usually has spin 2 and even parity would follow in those cases where the ground state and the first excited state are formed by a pair of identical nucleons in equivalent orbits, both for $j-j$ coupling and $L-S$ coupling. The excited state could also be caused by excitation of the even-even nucleus as a whole (liquid drop model). A more detailed experimental and theoretical study of this question seems desirable.

From a theoretical point of view, the most important results of our analysis of isomeric transitions seem twofold: Important objections to the strong spin-orbit coupling model have been removed, and the need for a refinement in the radiation probability formula has been pointed up by the recognition of the remarkable constancy of the squares of matrix elements for magnetic transitions and their large variability for electric transitions.

We should like to thank Doctors H. S. Snyder, G. Scharff-Goldhaber, E. J. Kelly, M. Neuman, and G. Snow of this laboratory, and J. Blatt of the University of Illinois for valuable discussions.

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[43] E. L. Brady and M. Deutsch, Phys. Rev. 78, 558 (1950). D. S. Ling and D. L. Falkoff, Phys. Rev. 74, 1224 (1948).

[44] D. E. Alburger and G. Friedlander, Phys. Rev. 81, 523 (1951). *Note added in proof:* Grace, Allen, West, and Halban, Proc. Phys. Soc. (London) 64, 493 (1951), have measured the internal conversion coefficient of this 803-kev γ-ray which is emitted following α-decay from Po^{210}. They find $\epsilon = 6.7$ percent, from which they conclude that this is an $M2$ transition. The theoretical values are $\beta_2 = 7.8$ percent, and $\alpha_3 = 2.1$ percent. Excited states formed by α-decay from an even-even nucleus should be expected to have even parity for even angular momentum and odd parity for odd angular momentum. The gamma-ray transitions from these states to the ground state should therefore be expected to be electric transitions.