tensities indicated by the measured curves are about a factor of two greater than the values given by the theoretical curves. There is earlier evidence[21] indicating that use of the Born approximation yields an underestimate of the bremsstrahlung cross section for electrons in this energy range. A detailed examination of this question by the use of thin targets is now in progress.[22] With regard to the angular distribution of the radiation, it is interesting to note the extent to which the angular diffusion of the electrons in the target smear the radiation pattern. This smearing is evident when one compares the intensity ratio at 0° and 90° for thin and thick targets; the Sauter formula gives an intensity ratio of about 200, while the thick target results give an intensity ratio of about three.

The writers wish to thank Dr. H. O. Wyckoff for his advice during the course of this work, and F. H. Attix for his help in carrying out the ionization chamber measurements.

[21] H. Klarmann and W. Bothe, Z. Physik **101**, 489 (1936).

[22] A preliminary report on these thin target measurements by Motz and Miller, to be published, indicates a similar disagreement between theory and experiment for 1-Mev electrons.

PHYSICAL REVIEW VOLUME 96, NUMBER 5 DECEMBER 1, 1954

Orbital Electron Capture in the Heaviest Elements*†

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(Received August 20, 1954)

Log*ft* values have been calculated for 30 orbital electron capture isotopes in the heaviest elements ($Z=89$–97). The average values of log*ft* products for negative beta particle transitions have been used to classify the electron capture transitions studied as to forbiddenness. A logarithmic plot of the electron capture partial half-life *versus* neutrino energy has been made for both the allowed and forbidden species. These diagrams can be used in the prediction of electron capture half-lives where one has some insight into the amount of decay energy available.

THE orbital electron capture process can be studied with particular effectiveness in the heaviest elements since decay energies may be calculated from closed decay cycles. Because of inherent experimental difficulties, only a limited number of decay energies for electron capture have been determined either from continuous gamma ray spectra or from competing positron emission of known energy. In the region of atomic number greater than 82, Seaborg and co-workers[1] have used closed decay cycles to calculate decay energies for a large number of electron capture isotopes. Thompson[2] and Feather,[3] in earlier studies of electron capture, have plotted half-life as a function of energy for a number of electron capture nuclides in the heavy region. From a consideration of this type of diagram, the nuclides were classified according to the allowed or forbidden nature of the transition. However, these correlations were limited by a lack of experimental data. Major and Biedenharn[4] have extended these studies to lighter nuclei wherever half-life, branching ratio, and transition energy are known. They conclude that the scatter of the data on such a diagram does not permit differentiation as to degrees of forbiddenness.

A more fundamental indication, the *ft* value, has been used in the present work to determine the nature of electron capture transitions. The appropriate value of the function f of energy and atomic number was calculated considering allowed electron capture from the K and L shells only using the formulas given by Marshak.[5] This value was multiplied by the electron capture half-life to form the *ft* product. Table I lists log*ft* values for nuclides whose electron capture decay schemes are known or can be inferred from the negative beta particle or alpha decay of an isotope to the same daughter nucleus. In certain cases where relative intensities of gamma and x-rays are not known, it has been assumed that the majority of the electron capture decay proceeds to the excited levels in the daughter nuclei. Log*ft* values calculated for these transitions will not be affected greatly by a certain amount of branching decay to the ground states of the daughter nuclei.

Another group of nuclides exists for which decay schemes are not known. Log*ft* values have been calculated for these isotopes under the assumption of ground state transitions. Obviously this assumption is not realistic, but it is the only method of treating the data

* Most of the material in this article is presented in greater detail in the Ph.D. thesis, R. W. Hoff, University of California Radiation Laboratory Declassified Document UCRL-2325, 1954 (unpublished).

† This work was performed under the auspices of the U. S. Atomic Energy Commission.

[1] Seaborg, Glass, and Thompson (to be published); R. A. Glass, Ph.D. thesis, University of California Radiation Laboratory Unclassified Document UCRL-2560, April 1954 (unpublished).

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

[3] N. Feather, Proc. Roy. Soc. (London) **A63**, 242 (1952).

[4] J. K. Major and L. C. Biedenharn, Phys. Rev. **94**, 779 (1954).

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

at the present time. These logft values are listed in Table II.

A more detailed grouping of beta transitions than those following from Gamow-Teller selection rules has been given by Mayer *et al.*[6] In this case the logft products for allowed transitions were noted to be in general less than 6.0. In addition, King and Peaslee[7] have recently observed that most first-forbidden transitions have logft values averaging 6.5 and 7.5 for $\Delta I=0$ or 1, respectively, and logf_1t values averaging 8.5 for $\Delta I=2$.

These average values of ft products for negative beta particle transitions are used to classify the electron capture transitions studied here. None of the above-mentioned nuclei are here classified as l-forbidden, since the logft limits for this type of transition are quite broad and knowledge of exact orbital assignments is lacking for the heavy elements. It is also noted that most of the nuclides can be considered as either allowed or first forbidden $\Delta I=0$, 1 yes.

TABLE I. Logft values for nuclides whose electron capture decay schemes are known or can be inferred.

Isotope	Available energy from closed cycles (Mev)	Level to which decay proceeds[a] (Mev)	Decay energy (Mev)	Partial electron capture half-life (sec)	Logft
Pa^{228}	2.07	1.03 (decay of Ac^{228})	1.04	8.1×10^4	6.6
Pa^{230}	1.32	0.94 (γ ray observed)	0.38	1.7×10^6	6.9
U^{231}	0.34	Ground state—50% 0.23—50% (decay of Th^{231})	0.34 0.11	7.4×10^5 7.4×10^5	6.4 4.7
Np^{232}	2.67	1.05 (γ ray observed, decay of Pa^{232})	1.62	7.8×10^2	5.1
Np^{233}	1.09	0.30 (conv. e^-'s observed, decay of Pa^{233})	0.79	2.1×10^3	4.8
Np^{234}	1.86	1.57[b] (γ ray observed)	0.29	3.8×10^5	6.1
Np^{235}	0.17	Ground state[b] (no γ rays observed)	0.17	3.5×10^7	6.6
Pu^{234}	0.48	Ground state[b] (no γ rays observed)	0.48	3.4×10^4	5.6
Am^{238}	2.26	1.03 (decay of Np^{238})	1.23	7.6×10^3	5.8
Am^{239}	0.78	0.277 (γ ray observed, decay of Np^{239})	0.50	4.3×10^4	5.7
Am^{240}	1.46	0.92—14%[c] 1.02—70% 1.40—15%	0.54 0.44 0.06	1.2×10^6 2.4×10^5 1.1×10^6	7.4 6.6 3.2
Am^{242m}	0.69	0.041[b] (conv. e^-'s observed)	0.65	2.6×10^5	6.7
Cm^{241}	0.89	0.47—28%[c] 0.59— 7% Ground state—65%	0.42 0.30 0.89	4.7×10^6 1.1×10^7 4.3×10^7	8.2 log$f_1t=6.5$ 8.2 log$f_1t=6.4$ 8.3 log$f_1t=7.7$
Bk^{245}	0.70	0.245[d] (γ ray observed)	0.46	4.3×10^5	6.7

[a] Data on decay schemes have been taken from Hollander, Perlman, and Seaborg, "Table of Isotopes," Revs. Modern Phys. **25**, 469 (1953) unless otherwise noted.
[b] Experimental work by authors.
[c] R. A. Glass, Ph.D. thesis, University of California Radiation Laboratory Unclassified document UCRL-2560, April, 1954 (unpublished).
[d] E. K. Hulet, Ph.D. thesis, University of California Radiation Laboratory Unclassified document UCRL-2283, July, 1953 (unpublished).

TABLE II. Logft values for nuclides whose electron capture decay schemes are not known.

Isotope	Decay energy (Mev)	Partial electron capture half-life (sec)	Logft
Ac^{223}	0.64	1.3×10^4	5.3
Ac^{224}	1.39	1.2×10^4	6.0
Th^{225}	0.55	4.8×10^3	4.7
Pa^{227}	1.08	1.5×10^4	5.9
Pa^{229}	0.37	1.3×10^5	5.8
U^{228}	0.30	2.8×10^3	3.8
U^{229}	1.29	4.4×10^3	5.6
Np^{236}	0.91	1.2×10^5	6.8
Pu^{232}	0.99	2.2×10^3	5.1
Pu^{235}	1.14	1.6×10^3	5.1
Pu^{237}	0.23	3.5×10^6	6.8
Am^{237}	1.48	4.7×10^3	5.9
Cm^{238}	1.12	1.0×10^4	6.0
Cm^{239}	1.79	1.1×10^4	6.4
Bk^{243}	1.46	1.7×10^4	6.5
Bk^{244}	2.20	1.8×10^4	6.8

The isotope Cm^{241} has logft values for its transitions that are large enough to suggest assignment of $\Delta I=2$, yes. It is more appropriate in the case of the pure Gamow-Teller $\Delta I=2$, yes transitions to use a special first-forbidden f_1 for the f_1t product.[5] These logf_1t values, listed in Table I, are somewhat lower than the average of 8.5 for negative beta particle emitters. This result indicates that $\Delta I=0$, 1 yes is a preferable assignment for the Cm^{241} decay.

The apparent lack of highly forbidden transitions is not surprising, since the precise amount of electron capture branching to various excited levels is often very difficult to determine and the highly forbidden transitions would be masked by the more predominant allowed decay. The logft values, 3.8 for U^{228} and 3.2 for Am^{240}, are definitely low even for allowed transitions in this region. However, a small increase in the calculated decay energies for U^{228} and Am^{240} would raise the ft values to within the limits for allowed electron capture.

For the isotopes studied, i.e., those with atomic number greater than 82, the nuclear shell model predicts that the odd proton and the odd neutron will generally be in orbitals of different parity, although the many low-energy $E1$ gamma transitions in the heavy region cast doubt on the generality of this parity change assumption. Ground state transitions would involve parity changes, and therefore allowed transitions would be expected to populate excited levels of daughter nuclei. In this region many odd-odd nuclei decay to highly excited levels in their even-even daughter nuclei. For example, Ac^{228}, Pa^{232}, Pa^{234}, Np^{234}, Np^{238}, Am^{240}, and others decay to levels at least one Mev above the ground state of the daughter nucleus. Therefore, it may be expected that transitions to highly excited levels will be observed when enough decay energy is available in

[6] Mayer, Moszkowski, and Nordheim, Revs. Modern Phys. **23**, 315 (1951); L. W. Nordheim, Revs. Modern Phys. **23**, 322 (1951).
[7] R. W. King and D. C. Peaslee, Phys. Rev. **94**, 1284 (1954).

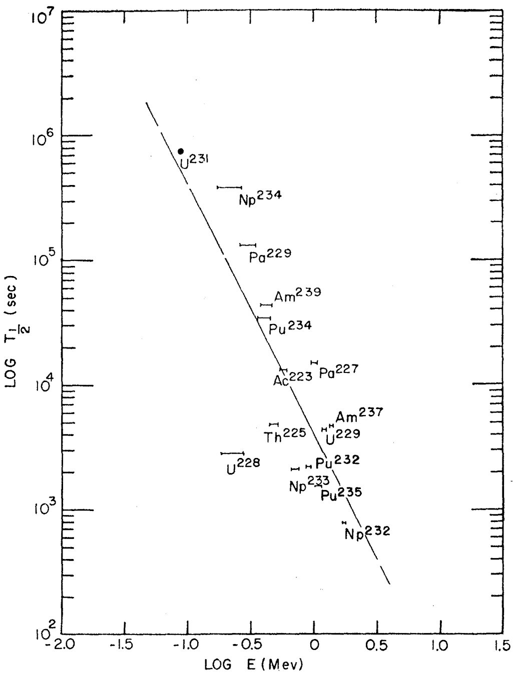

FIG. 1. Logarithm of the partial electron capture half-life *versus* logarithm of the neutrino energy for allowed electron capture.

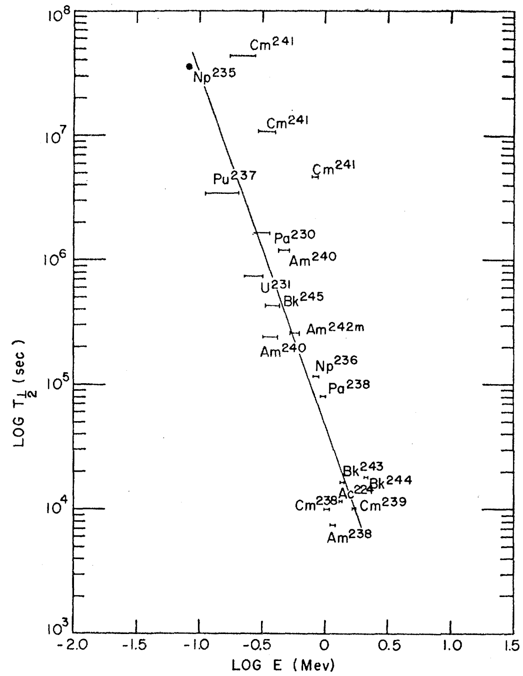

FIG. 2. Logarithm of the partial electron capture half-life *versus* logarithm of the neutrino energy for forbidden electron capture. (In the figure, Pa^{238} should read Pa^{228}.)

certain odd-odd nuclei for which no experimental data are yet available.

A plot of the logarithm of the partial electron capture half-life *versus* the logarithm of the neutrino energy for allowed species is shown in Fig. 1. This type of plot may be used with confidence, for the variation of electron capture probability with atomic number in this limited range is not great. The limits on the neutrino energy indicate K and L electron capture energies, the average decay energy lying somewhere between the limits, depending on the ratio of K to L electron capture. The theoretical expression for the probability of allowed electron capture predicts a slope of two for such a plot. A reference line has been drawn with the predicted slope. The data indicate a line of slope slightly greater than two.

A similar plot for the forbidden electron capture transitions is shown in Fig. 2. Although theory does not predict a unique slope in this type of plot for $\Delta I = 0, 1$ yes transitions, the slope should be between two and three. The data fit a line of slope of approximately three as indicated in the figure. Curium-241 with its larger $\log ft$ values falls well away from the line.

These diagrams can be used in the prediction of electron capture half-lives when one has some insight as to the amount of decay energy available. This is especially true in a search for new isotopes in the heaviest elements where electron capture energies may be calculated from closed-decay cycles. In addition, a continuation of this type of study may eventually lead to the prediction of decay schemes for new isotopes in the region.

The continued interest and helpful suggestions of Professor G. T. Seaborg throughout this investigation are gratefully acknowledged. The authors also wish to express appreciation to Dr. J. O. Rasmussen, Jr. for his most helpful discussion of the problem.