L-Subshell Ratios of Some Low-Energy $E2$ Transitions*

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L-subshell internal conversion ratios have been measured for low-energy $E2$ transitions in several deformed nuclei: Dy^{160} (86.74 keV), Er^{166} (80.57 keV), Tm^{169} (130.53 keV), Yb^{170} (84.23 keV), Os^{186} (137.15 keV), and Os^{188} (155.03 keV). The measurements were made with 50-cm radius, double focusing spectrometers at momentum resolutions better than 0.1%, and the ratios were determined with an accuracy of about 2%. In all but one of the six cases the L_2/L_3 ratios agree with theoretical values; however, the L_1/L_3 ratios in all cases are larger than theoretical values, with an average deviation of 6%. There is no immediately available explanation for this discrepancy.

FOR the determination of the multipolarities of nuclear electromagnetic transitions from internal conversion measurements one does not in general require great accuracy in the experimental data or in the theoretical coefficients with which the data are compared; the variation in conversion probability with multipole order is usually large. However, in those cases in which relatively small amounts of multipole admixture are to be determined or in which small nuclear or chemical effects are to be investigated, it becomes important to know accurately the coefficient values, or at least relative values, for pure normal[1] transitions. The accuracy of the values in the two major tabulations of theoretical conversion coefficients for the K and L shells currently available[2,3] is estimated by their authors to be about 2%.[3,4] Nevertheless, Novakov and Hollander[5] have pointed out that in some cases much larger discrepancies exist between the two tabulations.

The most recent accurate measurements of K-shell coefficients for pure unretarded transitions[6] agree with the theoretical values. On the other hand, discrepancies between measured and tabulated L-subshell conversion ratios for normal transitions have been noted by Herrlander and Graham,[7] and by several contributors to the 1965 Nashville Conference.[8] This information and a few additional measurements have recently been summarized by Hamilton.[9]

In this paper we report results of some careful measurements of L-subshell conversion ratios for pure electric quadrupole rotational transitions in deformed nuclei. Five of the transitions selected are $2+ \rightarrow 0+$ ground-state rotational band transitions; in Tm^{169} the transition occurs between a state of spin $\frac{7}{2}$ and one of spin $\frac{3}{2}$ in the $K=\frac{1}{2}$ rotational band. All these transitions proceed at faster than single-particle rates. The results of the measurements are compared with theoretical results obtained by interpolation.

EXPERIMENTAL METHODS

Thin uniform layers of the elements to be irradiated, either in metallic form or in the form of oxides,[10] were sublimed in vacuum and condensed onto thin pure aluminum foil. The thicknesses of these deposits varied from case to case, ranging from about 6 to about 45 $\mu g/cm^2$. Strips about 0.8 mm wide by 15 mm long were cut from the foils and irradiated either in the Brookhaven graphite research reactor ($\approx 10^{13}$ n/cm^2 sec) or in the reactor DR-2 at Risø, Denmark ($\approx 1.6\times 10^{14}$ n/cm^2 sec).

The two iron spectrometers used in this work are of

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[1] The term normal transition is employed to mean a transition which is not so highly retarded that dynamic nuclear structure effects [E. L. Church and J. Weneser, Ann. Rev. Nucl. Sci. **10**, 193 (1960)] are to be expected.
[2] L. A. Sliv and I. M. Band, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965), p. 1639.
[3] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958).
[4] L. A. Sliv and I. M. Band, *Coefficients of Internal Conversion of Gamma Radiation* (USSR Academy of Sciences, Moscow-Leningrad, 1958); also issued as Report 58ICCL1, University of Illinois, Urbana, Illinois (unpublished).
[5] T. Novakov and J. M. Hollander, Nucl. Phys. **60**, 593 (1964).
[6] For example, K.-E. Bergkvist and S. Hultberg, Arkiv Fys. **27**, 321 (1965) (Hg^{198}, 411.77-keV $E2$ transition); and P. Erman and S. Hultberg, Arkiv Fys. **30**, 101 (1965) (Dy^{160}, 86.74-keV $E2$ transition).
[7] C. J. Herrlander and R. L. Graham, Nucl. Phys. **58**, 544 (1964).
[8] R. Stepic, M. Bogdanovic, and M. L. Mladjenovic, in *Internal Conversion Processes*, edited by J. H. Hamilton (Academic Press Inc., New York, 1966), p. 507; S.-E. Karlsson, I. Andersson, Ö. Nilsson, G. Malmsten, and E. Aisenberg, *ibid.*, p. 513; W. H. Brantley, S. C. Pancholi, and J. H. Hamilton, *ibid.*, p. 535; J. H. Hamilton, B. van Nooijen, A. V. Ramayya, and W. H. Brantley, *ibid.*, p. 541. Also, private communications to the conference by T. Novakov and J. M. Hollander, by R. L. Graham and J. S. Geiger, and by T. Yamazaki and J. M. Hollander, *ibid.*, cf. pp. 512, 513.
[9] J. H. Hamilton, Phys. Letters **20**, 32 (1966).
[10] For the Yb^{169} sources, Yb_2O_3 enriched to 20% in Yb^{168}, was used. The material was obtained from Isotopes Division, U. S. Atomic Energy Commission, Oak Ridge, Tennessee.

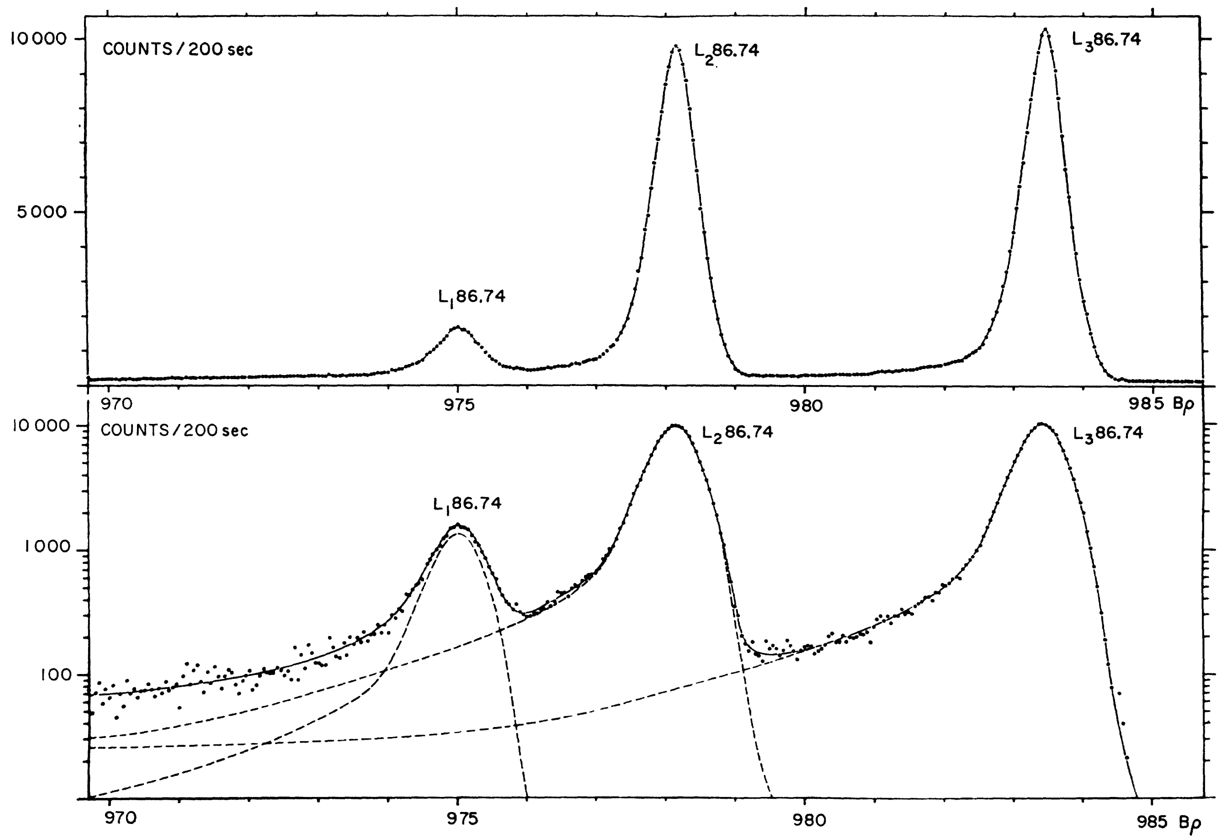

FIG. 1. *L*-subshell lines of the 86.74-keV transition in Dy^{160} following the decay of Tb^{160}. In the upper part of the figure the total count at each point is shown in a linear plot. In the lower part the flat background, taken from points above $B\rho=985$ G-cm, has been subtracted; the ordinate is on a logarithmic scale. The measurements were extended over a much larger $B\rho$ interval than is shown.

the Svartholm-Siegbahn type.[11] The instrument at Brookhaven has a side-window proportional counter detector for which dead time corrections are negligible. In the Stockholm spectrometer a G-M detector is employed; dead-time corrections at the highest count rates of these measurements did not exceed 1.5% and the uncertainty in the correction leads to a maximum uncertainty in the intensities of ≈0.2%. Because the *L*-multiplet components are so close to each other in energy no window transmission corrections were necessary. Line momentum widths observed ranged from ≈0.07% to ≈0.1% full width at half-maximum. Several sets of measurements were made for each transition studied. A typical spectrum, that for the 86.74-keV transition in Dy^{160}, is shown in Fig. 1.

At momentum values just above the multiplet structure the count rate due to natural background, gamma radiation from the source, and beta continuum was determined. This total background was subtracted from all points before further analysis. It may be noted that even at momentum values well below the multiplet structure tails of the lines persist, slowly changing in intensity. The intensity of such a tail relative to that at the peak of a line depends on source thickness, the nature of the source backing, and on the properties of the spectrometer itself. It is tempting to take the background under a multiplet to be a sloping line drawn from some point below the multiplet to a point above it, where the count rate is essentially constant. Such a procedure can easily lead to errors in the relative intensities derived for the multiplet components. In all spectra the L_3 line is least affected by overlap with the others, and a trial shape for the multiplet analysis was taken from it. The low-energy tail of L_3 under the L_2 and L_1 lines and that of L_2 under L_1 were determined essentially by the requirement that the final line shape deduced after iteration, used at the three line positions and arbitrarily adjusted in height at each position, reproduced the observed multiplet even in the region several line widths below the L_1 peak, where only overlapping low-energy tails contributed to the count rates. For convenience the line was taken to have the same momentum width for the three components; this simplification, which results in a slight decrease of the peak heights of L_1 and L_2 with respect to L_3, was compensated for by taking the final intensities as equal to the resolved peak heights divided by their $B\rho$ values. This procedure produces errors in the relative intensities of less than 0.5%. Differences in the natural widths and the small

TABLE I. Measured and theoretical values for the L-subshell conversion ratios of some $E2$ transitions.

Nucleus	Transition energy in keV[a]	Measured intensity ratios $R_1=L_1/L_3$	Measured intensity ratios $R_2=L_2/L_3$	Rel. exp. wt.[b]	Theoretical ratios[c] $(R_1)_{th}$	Theoretical ratios[c] $(R_2)_{th}$	Deviation in % $\left(\frac{R_1-(R_1)_{th}}{(R_1)_{th}}\right)\times 100$	Deviation in % $\left(\frac{R_2-(R_2)_{th}}{(R_2)_{th}}\right)\times 100$
Dy^{160}	86.74	0.130	0.973	1				
		0.130	0.961	1				
		Av 0.130±0.002[d]	Av 0.967±0.014		0.122	0.961	6.6±2.0[e]	0.6±1.8
Er^{166}	80.57	0.0866	0.945	1				
		0.0854	0.947	3				
		0.0861	0.941	3				
		Av 0.0859±0.0015	Av 0.944±0.014		0.0800	0.947	7.4±2.1	0.0±1.8
Tm^{169}	130.53	0.296	1.15	1				
		0.287	1.12	1				
		Av 0.292±0.005	Av 1.14±0.02		0.278	1.14	5.0±2.0	0.0±2.0
Yb^{170}	84.23	0.0813	0.998	1				
		0.0806	0.993	1				
		Av 0.0810±0.0012	Av 0.996±0.014		0.0752	0.987	7.7±1.9	0.9±1.7
Os^{186}	137.15	0.206	1.30	1				
		0.200	1.28	3				
		0.198	1.28	3				
		Av 0.200±0.005	Av 1.28±0.02		0.186	1.28	7.5±2.9	0.0±1.9
Os^{188}	155.03	0.272	1.39	1				
		0.268	1.38	3				
		0.264	1.35	3				
		0.265	1.39	3				
		Av 0.266±0.006	Av 1.38±0.02		0.256	1.33	3.9±2.6	3.8±1.9

[a] References for the transition energy values may be found in *Nuclear Data Sheets*, compiled by K. Way, *et al.* (Publishing & Printing Office, National Academy of Sciences—National Research Council, Washington, D. C.).
[b] Relative weights assigned to the individual measurements are based mainly on counting statistics and source quality.
[c] For convenience, only the ratios derived from the tables of Sliv and Band (Ref. 2) are given. Values were interpolated also from the tables of Rose (Ref. 3); they differed from those of Sliv and Band by 2–3% in an apparently random manner. For the Tm^{169} case values have been calculated also by Seltzer and Hager [private communication; see also Phys. Letters **18**, 163 (1965)]; their values are 0.272 and 1.14.
[d] The assigned uncertainties reflect not only the deviations of the individual results from the weighted mean but also an estimate of the uncertainty in the method of analysis.
[e] The uncertainties in the deviations include both the experimental uncertainty and an uncertainty, taken to be 1%, due to interpolation of the theoretical values.

differences in energy degradation result in errors which are completely negligible.

RESULTS AND DISCUSSION

The experimental results and their relationship with the theoretical coefficients are shown in Table I. Coefficients at the required energy values were obtained from the tabulated theoretical coefficients by a four-point log-log Lagrange interpolation.

With one exception, the theoretical L_2/L_3 values agree well with those determined in this work; it is clear, however, that this is not the case for L_1/L_3. The average deviation for L_1/L_3 is (6.4±1.0)%. No obvious trend with atomic number, deformation, or energy is discernible.[12,13]

From these results one cannot tell whether the L_1/L_3 deviations represent theoretical L_1 results which are too small, whether they represent theoretical L_2 and L_3 results which are too large, or both. It may be noted that the deviations, though definite, are not as large as have sometimes been reported.[14] It is not clear whether the discrepancies are due to defects in the atomic models used for calculations of internal conversion or to approximations used in the computations. Although in some Z and energy regions disagreement between the Rose and Sliv calculations exists,[5,9] for the cases studied here, the two and, in one instance, three sets of calculations, all based on essentially the same model, do give very nearly the same results. Thus it may be that there are some small defects in the internal conversion model.

ACKNOWLEDGMENTS

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[11] See, for example, K. Siegbahn, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965), p. 96.

[12] In order to account for the deviation in the Tm^{169} case by admixture of $M3$ radiation to the predominantly $E2$ transition, the $M3$ transition probability would have to be about 10^7 times the Weisskopf estimate.

[13] We have recently learned that measurements similar to those reported here have been done by W. Gelletly, J. S. Geiger, and R. L. Graham, and by R. Hager and E. Seltzer. We thank these investigators for their communications. *Note added in proof:* see W. Gelletly, J. S. Geiger, and R. L. Graham, Bull. Am. Phys. Soc. **11**, 352 (1966).

[14] The previous experimental results have been collected by Hamilton, Ref. 9.