E0-E2-M1 multipole admixtures of transitions in even-even nuclei

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Measurements of E2/M1 and E0/E2 multipole mixing ratios of transitions in even-even nuclei have long provided important tests of nuclear models. The experimental data for transitions in even-even nuclei have been critically surveyed to provide the most accurate results for comparisons with theoretical calculations. The theoretical approaches to the calculations of these mixing ratios on the bases of different nuclear models are considered and compared with experimental data. The variations in signs and magnitudes of the E2/M1 mixing ratios from nucleus to nucleus for the same class transitions and within a given nucleus for transitions from different spin states suggest that a microscopic approach is needed to explain the data theoretically. The pairing-plus quadrupole model has achieved the first successes in predicting these variations, primarily in the osmium to platinum region.

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I. INTRODUCTION

When gamma-ray and conversion electron emission occur in the decay of an excited nuclear state, more than one multipole radiation is often allowed by the selection rules on the nuclear spins and parities. While any multipole order between the sum and difference of the initial and final nuclear spins is allowed, the strong dependence of the transition probabilities on the angular momentum carried off restricts the observable orders to the lowest ones. For example, with only a very few recently discovered exceptions, in transitions where multipole orders $\lambda \geq 1$ are allowed and the parity changes, the E1 radiation totally dominates with $M2 \leq 1\%$ [see Hamilton (1972a)]. However, when the selection rules allow, E2 radiation often dominates the M1 component. The domination of the E2 radiation occurs because nuclear structure effects override the angular momentum dependence of the transition probabilities. Thus experimental determinations of the admixtures of E2/M1 radiations in nuclear transitions, particularly in even-even nuclei, have provided for over two decades many significant tests of nuclear models. Because of the importance of these data, there have been periodic surveys of E2/M1 mixing ratios and theoretical studies to predict or explain these data in even-even nuclei: Coleman (1958), Davydov and Filip-

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pov (1958), Malik (1959), Van Patter (1959), Grigoviev and Avotina (1960), Mallman (1961), Tamura and Yoshida (1962), Grechukhin (1963), Potnis and Rao (1963), Bès, *et al.* (1965), Greiner (1966), Grechukhin (1969), Kumar (1969), Hamilton (1971), Krane and Steffen (1971), Bodenstedt (1972), Hamilton (1972a, 1972b), and Krane (1975, 1977, 1978, 1980).

As a starting point, electromagnetic transition probabilities often are compared to estimates based on a single-particle shell model. Single-particle E2 and M1 "Weisskopf" estimates (Blatt and Weisskopf, 1952) show the M1 strength as totally dominating. The "Weisskopf Unit" for the E2/M1 strengths is $\sim 1/400$ for nuclei with $A \sim 200$. The corresponding experimental values for transitions from the second $2^{+\prime}$ to first excited 2^+ states in even-even nuclei typically range from 1 to 20. This striking reversal of the relative strengths of E2,M1 transitions is explained qualitatively by the collective nuclear model developed by Bohr (1952), Bohr and Mottelson (1953, 1975), and others. The E2 transitions are enhanced because the collective E2 operator is proportional to the charge of the total nucleus instead of just the charge of a single proton. The M1 transitions are hindered (in fact, prohibited in the simplest form of the collective vibrational and rotational models) because the leading term of the collective M1 operator is proportional to the total angular momentum of the nucleus. Since nuclear angular momentum is a good quantum number, only the diagonal matrix elements (magnetic moments) are nonzero. Grechukhin (1969) in his review used the E2/M1 mixing ratio as a criterion for testing for collective effects in the structure of nuclear states.

Among the important early tests of the collective model for deformed nuclei were studies which established that the M1 admixtures in transitions from the 2^+, $K=2$ gamma-type vibrational states to the 2^+, $K=0$ ground-band rotational states in deformed nuclei were small, $<5\%$ [see the reviews of Bodenstedt (1972) and Hamilton (1971)]. These data verified the predictions of Bohr and Mottelson (1955) that the transitions between the $K=2$ and $K=0$ states should be E2 radiations, since the $K=2$ states were described as quadrupole vibrations of the nucleus.

Since 1967, the use of Ge(Li) detectors in the measurements of E2/M1 admixtures has dramatically increased the quantity and quality of the data as noted in the earlier surveys of one of our group, Hamilton (1971, 1972a). The multipole admixtures of weak transitions in very complex decays can be carried out with good accuracy so that new sensitive tests of the predictions of nuclear models can be made. These new data have challenged some older ideas and called forth new approaches. For example, in spherical even-even nuclei, the $2^{+\prime} \rightarrow 2^+$ transitions are not pure E2 as the first vibrational model predicted, but often have up to 30% M1 admixtures. The rotational model, extended by Davydov and Filipov (1958), does give more nearly the right order of magnitude in the case of deformed nuclei (predicted value for the relative E2/M1 strengths is $\sim 20/1$ for $A \sim 180$), but it does not give correct variations from nucleus to nucleus.

A better understanding of the measured E2/M1 mixing ratios has required further refinements of nuclear models. In particular, the variations in the signs of δ(E2/M1) values from nucleus to nucleus and from one state to another in the same nucleus provide some of the most sensitive tests of nuclear models. Variations in the sign of δ are particularly striking in the osmium, platinum region (Hamilton and Davies, 1968; Krane and Steffen, 1971). Among the many versions of the collective model which have been developed during the past 20 years, the most successful is the microscopic pairing-plus-quadrupole model developed by Kumar and Baranger (1968) and extended by Kumar (1969, 1975), which is able to predict such variations of signs. The magnitudes of δ values are also given within experimental errors in these nuclei. However, the same model does not work as well in the more deformed samarium, gadolinium region (Kumar, 1974; Gupta *et al.*, 1977). Good results for the δ values of Os-Pt nuclei have also been reported by Maruhn-Rezwani *et al.* (1975). A brief discussion of their nonmicroscopic model is given in Sec. III. C. 4.

In deformed nuclei anamolous E2 branching ratios for transitions from the beta-type vibrational levels (Riedinger *et al.*, 1967) raised serious questions for the Bohr and Mottelson (1953) collective model (Mottelson, 1968). Suggested explanations included large (50%) M1 admixtures in $\Delta I=0$ transitions from these β vibrational states. Subsequent measurements made possible by Ge(Li) detectors excluded these M1 admixtures in transitions from the 2^+_β and 4^+_β states and called for more microscopic theories [see Hamilton (1972c)]. Now M1 admixtures in transitions out of the β and γ vibrational levels have been measured up to spin 8 in beta (Ejiri and Hagemann, 1971) and gamma bands (Baker *et al.*, 1975). These data provide significant tests of the rotational model, which we shall discuss in Sec. V.

With much new experimental and theoretical work being carried out, particularly on E2/M1 mixing ratios in even-even nuclei, a critical survey of both areas is needed to point the way for further work. As our survey will show, there have been problems with older data from NaI detectors, as well as with the newer Ge(Li) ones. The areas where such problems are likely to occur are described. Because of the importance of accurate data for comparison with microscopic calculations, a critical analysis of each experimental result was made in order to recommend adopted values for comparison with theoretical calculations. The theoretical problems of the sign conventions for δ and the validity of various theoretical approaches from both a theoretical perspective and a comparison with experimental data are discussed.

A natural extension of earlier surveys is to include data on E0/E2 admixtures in $\Delta I=0$ transitions. Experimental data on these admixtures likewise provide important tests of nuclear models and microscopic calculations. Earlier reviews of the experimental data on E0 transi-

tions have been given by Hamilton (1972a), Aldushchenkov and Voinova (1973), and Voinova (1976).

In the second section the definition of δ and sign conventions are presented. Next, the various theoretical approaches to the E0/E2 and E2/M1 mixing ratios are discussed. Section IV presents a critical survey of the available experimental data to early 1979, and the final section makes some comparisons of the experimental and theoretical results through 1980.

II. DEFINITIONS AND SIGN CONVENTIONS

A. The E2, M1 mixing ratio, δ(E2/M1)

The E2,M1 mixing ratio has been defined by Biedenharn and Rose among others (Biedenharn and Rose, 1953; Biedenharn, 1960; Rose and Brink, 1967; Krane and Steffen, 1970). All of these definitions differ in the sign conventions. Before reviewing these sign conventions, we discuss the definition of δ^2 which is standard.

Consider γ-ray transitions from an initial nuclear state with angular momentum J_1 and parity Π_1 to a final state (J_2,Π_2). Let the initial and final states be such that both E2 and M1 transitions are allowed $(J_1+J_2\geq 2,\ |J_1-J_2|\leq 1,\ \Pi_1\Pi_2=+1)$. Then the square of the E2,M1 mixing ratio is defined as (the parity indices are suppressed)

$$\delta^2(\mathrm{E2/M1};J_1\rightarrow J_2)=\frac{\text{No. of E2 transitions/sec}}{\text{No. of M1 transitions/sec}}=\frac{T(\mathrm{E2};J_1\rightarrow J_2)}{T(\mathrm{M1};J_1\rightarrow J_2)}\ , \tag{2.1}$$

where $T[\mathrm{E(M)}\lambda]$ is the γ-ray transition probability for a given E(M)λ summed over the magnetic substates of the photon and of the final nuclear state. The experimental results are often expressed in terms of the reduced transition probability, $B[\mathrm{E(M)}\lambda]$, which is defined in terms $T[\mathrm{E(M)}\lambda]$ as [see, for example, Bohr and Mottelson (1969)]

$$T[\mathrm{E(M)}\lambda;J_1\rightarrow J_2]=\frac{8\pi(\lambda+1)}{\lambda[(2\lambda+1)!!]^2}\frac{1}{\hbar}q^{(2\lambda+1)}B[\mathrm{E(M)}\lambda;J_1\rightarrow J_2]\ , \tag{2.2}$$

where $q=[E_\gamma/(\hbar c)]$ is the wave number for the photon. The reduced transition probability is written in terms of nuclear matrix elements as

$$B[\mathrm{E(M)}\lambda;J_1\rightarrow J_2]=\sum_{\mu M_2}|\langle J_2M_2|\mathscr{M}[\mathrm{E(M)}\lambda,\mu]|J_1M_1\rangle|^2=(2J_1+1)^{-1}|\langle J_2||\mathscr{M}[\mathrm{E(M)}\lambda]||J_1\rangle|^2\ , \tag{2.3a}$$

where $\langle||\ \ ||\rangle$ is a reduced matrix element, and $\mathscr{M}[\mathrm{E(M)}\lambda]$ is the electromagnetic operator defined by Bohr and Mottelson (1953, 1969) as

$$\mathscr{M}(\mathrm{E}\lambda,\mu)=\sum_k e[\tfrac{1}{2}-t_z(k)]r_k^\lambda Y_{\lambda\mu}(\theta_k,\phi_k)\ , \tag{2.3b}$$

$$\mathscr{M}(\mathrm{M}\lambda,\mu)=\frac{e\hbar}{2Mc}\sum_k\left[g_s(k)\mathbf{s}_k+\frac{2g_l(k)}{\lambda+1}\mathbf{l}_k\right]\cdot\nabla_k[r_k^\lambda Y_{\lambda\mu}(\theta_k,\phi_k)]\ , \tag{2.3c}$$

with $t_z=1/2(-1/2)$ for a neutron (proton). Thus the square of the mixing ratio can be rewritten as

$$\delta^2(\mathrm{E2/M1};J_1\rightarrow J_2)=\frac{3}{100}q^2\frac{B(\mathrm{E2};J_1\rightarrow J_2)}{B(\mathrm{M1};J_1\rightarrow J_2)}=\frac{3}{100}q^2\frac{|\langle J_2||\mathscr{M}(\mathrm{E2})||J_1\rangle|^2}{|\langle J_2||\mathscr{M}(\mathrm{M1})||J_1\rangle|^2}\ . \tag{2.4}$$

Since we are free to choose either sign for the square root of the right-hand side of Eq. (2.4) or (2.1), it is purely a matter of convention which sign is chosen for defining δ. Of course, while comparing a certain experimental value with theory or with other experiments, we must make certain that the same sign convention has been employed. In any case, however, it is a nontrivial problem! (1) The sign of the theoretical δ depends on the sign conventions employed for defining (a) the E(M)λ operators, and (b) the reduced matrix elements (fortunately, it does not depend on the phase conventions employed for the nuclear wave functions, because each wave function appears twice in the definition of δ). (2) The sign of the experimental δ depends on the sign conventions employed for (a) defining the axis of alignment with respect to which the γ-ray angular distribution is measured, and (b) the geometrical factors such as Clebsch-Gordan coefficients and Racah coefficients that enter the expression employed for the expansion of the angular distribution probability in terms of various polynomials.

We adopt the definition of Krane and Steffen (1970) for the sign of δ, that is, choose the positive root of the right-hand side of Eq. (2.4),

$$\delta(\mathrm{E2/M1};J_1\rightarrow J_2)=\frac{\sqrt{3}}{10}q\frac{\langle J_2||\mathscr{M}(\mathrm{E2})||J_1\rangle}{\langle J_2||\mathscr{M}(\mathrm{M1})||J_1\rangle}\ . \tag{2.5}$$

Note that the matrix elements of Eq. (2.5) follow the sign conventions of Bohr and Mottelson. They do *not* include the i^λ factor which is often included in the M(E2) matrix elements used in the analysis of Coulomb excitation data. For the reader's convenience, we rewrite Eq. (2.5) in the units employed most commonly for the quantities on the right-hand side of the equation,

$$\delta(\mathrm{E2/M1};J_1\rightarrow J_2)=0.835E_\gamma\ (\text{in MeV})\ \frac{\langle J_2||\mathscr{M}(\mathrm{E2})||J_1\rangle\ \text{in exb}}{\langle J_2||\mathscr{M}(\mathrm{M1})||J_1\rangle\ \text{in nm}}\ , \tag{2.6}$$

where E_γ is the γ-ray energy. The δ value is dimensionless.

The E2/M1 mixing ratios are deduced experimentally from an analysis of the angular distribution of the emitted (absorbed) γ rays. The angular distribution probability depends on the way the axis of alignment is defined. Some of the methods employed for this purpose are (Rose and Brink, 1967) (1) particle capture, (2) a particle-particle reaction, and (3) observation of a γ ray originating from a randomly populated state and followed by further γ rays.

The most common method belongs to class (3) and consists of the measurement of the angular distribution of γ rays emitted according to the scheme

$$J_1 \xrightarrow[\gamma_1]{} J_2 \xrightarrow[\gamma_2]{} J_3 \ .$$

The corresponding relation for the angular distribution probability is

$$W(\theta)=\sum_{\Lambda=\text{even}} B_\Lambda(\gamma_1)A_\Lambda(\gamma_2)P_\Lambda(\cos\theta) \ . \tag{2.7}$$

The orientation parameter, B_Λ, and the directional distribution coefficient, A_Λ, are given by Krane and Steffen (1970):

$$\begin{aligned} B_\Lambda(\gamma_1)=&[1+\delta^2(\gamma_1)]^{-1}[F_\Lambda(11J_1J_2) \\ &-2\delta(\gamma_1)F_\Lambda(12J_1J_2) \\ &+\delta^2(\gamma_1)F_\Lambda(22J_1J_2)] \ , \end{aligned} \tag{2.8a}$$

$$\begin{aligned} A_\Lambda(\gamma_2)=&[1+\delta^2(\gamma_2)]^{-1}[F_\Lambda(11J_3J_2) \\ &+2\delta(\gamma_2)F_\Lambda(12J_3J_2) \\ &+\delta^2(\gamma_2)F_\Lambda(22J_3J_2)] \ . \end{aligned} \tag{2.8b}$$

The geometrical factors $F_\Lambda(\lambda\lambda' J' J)$ have been defined and tabulated by Frauenfelder and Steffen (1965). The relations (2.8) refer to the case of emission ($E_i > E_f$).

For readers who wish to use the tables of Rose and Brink (1967), we give the corresponding relations for B_Λ and A_Λ,

$$\begin{aligned} B_\Lambda(\gamma_1)=&[1+\delta^2(\gamma_1)]^{-1}[R_\Lambda(11J_2J_1) \\ &\pm 2\delta(\gamma_1)R_\Lambda(12J_2J_1) \\ &+\delta^2(\gamma_1)R_\Lambda(22J_2J_1)] \ , \end{aligned} \tag{2.9a}$$

$$\begin{aligned} A_\Lambda(\gamma_2)=&[1+\delta^2(\gamma_2)]^{-1}[R_\Lambda(11J_2J_3) \\ &\mp 2\delta(\gamma_2)R_\Lambda(12J_2J_3) \\ &+\delta^2(\gamma_2)R_\Lambda(22J_2J_3)] \ , \end{aligned} \tag{2.9b}$$

where the upper sign refers to emission ($E_i > E_f$) and the lower sign to absorption ($E_i < E_f$), and δ has been defined by Eq. (2.5). We have taken the point of view that instead of changing the definition of δ for different conventions connected with different experimental situations, the appropriate changes should be made in the corresponding angular distribution relations. In rewriting Eqs. (2.9), as compared to Rose and Brink (1967), we have employed the following relations:

$$[R_\Lambda(\lambda\lambda' J' J)]_{RB}=(-1)^{\lambda-\lambda'+\Lambda}[F_\Lambda(\lambda\lambda' J' J)]_{FS} \ , \tag{2.10a}$$

$$[T^e_{\lambda\mu}]_{RB}=\pm\left[\frac{2\pi(\lambda+1)}{\lambda(2\lambda+1)}\right]^{1/2}\frac{q^\lambda}{(2\lambda-1)!!} \times[i^\lambda \mathcal{M}(\mathrm{E}\lambda,\mu)]_{BM} \ , \tag{2.10b}$$

$$[T^m_{\lambda\mu}]_{RB}=\left[\frac{2\pi(\lambda+1)}{\lambda(2\lambda+1)}\right]^{1/2}\frac{q^\lambda}{(2\lambda-1)!!} \times[i^{\lambda-1} \mathcal{M}(\mathrm{M}\lambda,\mu)]_{BM} \ , \tag{2.10c}$$

$$\langle J_2 \| T_\lambda \| J_1\rangle_{RB}=(2J_2+1)^{-1/2}\langle J_2 \| T_\lambda \| J_1\rangle_{BM} \ , \tag{2.11}$$

where the $+(-)$ sign in Eq. (2.10b) refers to emission (absorption). This sign difference arises because the E2 operator defined by Rose and Brink depends on the momentum operator or, alternatively, on the commutator of the interaction Hamiltonian with $r^2\ Y_{\lambda\mu}$ (Rose and Brink 1967, p. 314).

Krane and Steffen have stressed that the initial state must be written (if one is to follow their convention) on the right, and the final state on the left of the matrix element $\langle \| \ \| \rangle$ employed in a relation like (2.5). However, it seems to us that this convention (or the opposite one) matters only while taking the expectation value of a commutator of the type mentioned above. It should *not* affect the definition or the sign convention employed for δ. If we interchange $J_1 \leftrightarrow J_2$, *both* the E2,M1 matrix elements are modified by the same phase factor $(-)^{J_1-J_2}$. Hence, there is no change in the δ value.

The definition of the δ value discussed above has been related to that of Biedenharn (1960) by Rose and Brink (1967), and to that of Biedenharn and Rose (1953) by Krane and Steffen (1970). It seems that in order to have the same forms for B_Λ, A_Λ of Eq. (2.7), Biedenharn and Rose (1953) defined δ in such a way that its sign depended on whether one was analyzing the first (γ_1) or the second (γ_2) γ ray of a sequential decay.

In order to avoid some of the mystery and confusion that exists concerning the sign of the mixing ratios, it seems to us desirable to keep the definition of δ fixed and make the changes required by different experimental situations in the angular correlation relations. The most general relations, as well as some of the special cases, have been discussed by Rose and Brink (1967). However, their definition of δ appears to have different signs for emission and absorption (because of the relation 2.10b). Hence some care must be exercised in using their relations.

For convenience we note that

$$\delta_{KS}(\gamma_1)=-\delta_{BR}(\gamma_1)=-\delta_{RB}(\gamma_1) \ ,$$

$$\delta_{KS}(\gamma_2)=\delta_{BR}(\gamma_2)=-\delta_{RB}(\gamma_2) \ .$$

B. The E0, E2 mixing ratio, ε(E0/E2)

The square of the E0,E2 mixing ratio has been defined by Church and Weneser (1958) as ($J_1+J_2\geq 2$, $J_1=J_2$, $\Pi_1\Pi_2=+1$)

$$q^2[(\mathrm{E0}/\mathrm{E2});J_1\to J_2]=\frac{\text{No. of internal conversion electrons/sec}}{(\text{E2, }K\text{-shell internal conversion coefficient})\times(\text{No. of E2 transitions/sec})}$$
$$=\frac{T(\mathrm{E0};J_1\to J_2)}{\alpha_K(\mathrm{E2})T(\mathrm{E2};J_1\to J_2)}\ . \tag{2.12}$$

The E0 transition probability, T(E0), depends on the electronic wave funtions as well as the nuclear wave functions and is written as

$$T(\mathrm{E0};J_1\to J_2)=\Omega_K\langle J_2\,|\,\mathscr{M}(\mathrm{E0})\,|\,J_1\rangle^2$$
$$=\Omega_K\rho^2(\mathrm{E0};J_1\to J_2)\ , \tag{2.13a}$$

where Ω_K is an electronic factor defined and given by Church and Weneser (1956); $\mathscr{M}$(E0) is the electric monopole operator also defined by them as

$$\mathscr{M}(\mathrm{E0})=R_0^{-2}\sum_k e\left[\tfrac{1}{2}-t_z(k)\right]r_k^2\ , \tag{2.13b}$$

where R_0 is the nuclear radius; and ρ(E0) is the E0 matrix element which contains all the nuclear information needed for a E0 transition.

The sign of the mixing ratio, q(E0/E2), depends on the purely arbitrary choice of the sign of the square root of the right-hand side of Eq. (2.12). Adopting the sign convention of Church and Weneser (1958), and putting in the various definitions, we get (a possible sign change for absorption, in the conventional formulation, has been discussed in Sec. II. A).

$$q(\mathrm{E0}/\mathrm{E2};J_1\to J_2)$$
$$=2.86\times10^{-7}\left[\frac{\Omega_K\ (\text{in sec}^{-1})}{\alpha_K(\mathrm{E2})(E_\gamma\ \text{in MeV})^5}\right]^{1/2}$$
$$\times\frac{\varepsilon(\mathrm{E0}/\mathrm{E2};J_1\to J_2)}{R_0^2(\text{in b})}\ , \tag{2.14}$$

where

$$\varepsilon(\mathrm{E0}/\mathrm{E2};J_1\to J_2)$$
$$=-(2J_1+1)^{1/2}$$
$$\times\rho(\mathrm{E0};J_1\to J_2)eR_0^2/\langle J_2\,|\,|\mathscr{M}(\mathrm{E2})|\,|\,J_1\rangle\ , \tag{2.15}$$

and R_0 is the nuclear radius. The reduced E0/E2 mixing ratio, ε(E0/E2), is defined (Kumar, 1975) to have the *same sign as q*. The square of this ratio equals the *dimensionless* ratio defined by Rasmussen (1960),

$$X(\mathrm{E0}/\mathrm{E2};J_1\to J_2)=\varepsilon^2(\mathrm{E0}/\mathrm{E2};J_1\to J_2)\ . \tag{2.16}$$

In the case of $0'\to0$ transitions, only the E0 multipole is allowed. However, even in such cases a X value is often defined where the E2 matrix element refers to a $0'\to2$ transition. Since the quantities ε and X do not depend on the electronic factors and transition energies, they are more useful for comparing with nuclear models.

We stress again that in order for the signs of the mixing ratios to have physical meanings (and in order to avoid some of the the confusion in comparing the results of different experiments), the angular correlation relations must be defined in such a way that the sign of the resultant mixing ratio does not depend on the experimental method. If it is argued that it is a matter of defining the electromagnetic operator, then the definition where the sign of a matrix element depends on the sign of (E_i-E_f) does not make much sense, since $E_i-E_f=0$ for the static matrix elements.

The mixing ratios defined above are invariant under the interchange of initial and final states.

III. COLLECTIVE AND MICROSCOPIC MODEL PREDICTIONS OF MIXING RATIOS

Although a large number of models and submodels have been developed and applied to the study of energy levels, B(E2) values, quadrupole moments, and magnetic moments, only a few have been employed for predicting the mixing ratios. This is understandable because until recently the systematics of the experimental mixing ratios has been comparatively incomplete and because the calculation of the mixing ratio is more complicated (especially keeping track of the various signs!). We shall consider below only those model aspects which are useful for our study of E2/M1 and E0/E2 mixing ratios in even-even nuclei.

A. Single-particle shell model (Weisskopf unit)

1. δ(E2/M1)

For comparison with the observed electromagnetic transition rates, the Weisskopf Unit (Blatt and Weisskopf, 1952) based on the single-particle shell model is often employed. This unit is obtained (Bohr and Mottelson, 1969) by (1) replacing the radial integrals of r^λ between two shell model, single-particle states by the values $3(\lambda+3)^{-1}R_0^\lambda$, as would be appropriate for a constant wave function extending out to radius R_0, (2) evaluating the vector addition coefficients for the transi-

tion $\lambda+\frac{1}{2}\rightarrow\frac{1}{2}$, and (3) replacing the factor $\lambda^2[g_s-2(\lambda+1)^{-1}g_l]^2$ entering the $B(M\lambda)$ expression by the value 10. With a nuclear radius of $R_0=1.2A^{1/3}$ fm, one gets

$$B_W(E\lambda)=\frac{(1.2)^{2\lambda}}{4\pi}\left[\frac{3}{\lambda+3}\right]^2 A^{2\lambda/3}e^2\,(\mathrm{fm})^{2\lambda},$$

$$B_W(M\lambda)=\frac{10}{\pi}(1.2)^{2\lambda-2}\left[\frac{3}{\lambda+3}\right]^2 A^{(2\lambda-2)/3}(\mathrm{nm})^2(\mathrm{fm})^{2\lambda-2}. \tag{3.1}$$

By combining Eqs. (2.3), (2.6), and (3.1), we get a "Weisskopf Unit" for the magnitude of the mixing ratio,

$$|\delta_W(E2/M1)|=1.521\times10^{-3}E_\gamma\,(\text{in MeV})A^{2/3}. \tag{3.2}$$

For a typical value of $E_\gamma=1$ MeV, the Weisskopf Unit for $|\delta|$ equals 0.007, 0.021, 0.033, 0.052 for $A=10$, 50, 100, 200, respectively.

The single-particle model relation (3.2) indicates that the M1 mode of γ-ray emission predominates over the E2 mode. The experimental $\delta(E2/M1)$ values, however, provide a striking contrast to the above prediction of the shell model: a typical $|\delta|$ value lies in the range $1-10$. The rotational limit of the collective model provides the opposite limit for $|\delta|$ (see Sec. III.C 1). Grechukhin (1969) has argued that the δ value is an important measure of nuclear collectivity.

2. ε(E0/E2)

A single-particle estimate for the E0 matrix element, $\rho(E0)$ [obtained from the estimates given by Bohr and Mottelson (1975) for $m(E0)=eR^2\rho$, R being the nuclear radius], is $0.7A^{-1/3}$. By using this estimate as a "Weisskopf Unit," and the usual Weisskopf Unit for E2 transitions (Eq. 3.1), the "Weisskopf Unit" for the E0/E2 mixing ratio is found to be

$$|\varepsilon_W(E0/E2)|=4.1A^{-1/3}. \tag{3.3}$$

The experimental values seldom exceed the single-particle estimate of Eq. (3.3). Predictions of ε based on the rotational model are somewhat too large in the case of β-band to g-band transitions (see Sec. III.C.3). Rasmussen (1960) has argued that the ε value (or $X=\varepsilon^2$) can be employed to identify states of the β vibrational band. This was confirmed by Hamilton *et al.* (1966) in studies of ^{154}Gd. More recently in studies of ^{178}Hf, Hamilton *et al.* (1974) have shown that the situation is more complex than originally thought. In ^{178}Hf, we found that X was larger for the 2^+-2^+ decay of a two quasiparticle state at 1276 keV than for the more collective [based on the measured $B(E2:2-0)$ values (Ronningen *et al.*, 1977] 1496-keV 2^+ state (Hamilton *et al.*, 1974). Thus X is an important but not unique signature of a beta band.

B. Rotational model

Davydov and Filippov (1958) have extended the rotational model of Bohr and Mottelson (1952, 1953) and applied it to the problem of E2/M1 mixing ratios. The low-lying states of an even-even nucleus are described in terms of *rotations without change of shape.* The nuclear shape is defined in the intrinsic (rotating) frame by two variables β and γ, where β gives the magnitude of nuclear deformation and γ gives deviations from axial symmetry ($\gamma=0°$, $120°$, ... for prolate shapes; $\gamma=60°$, $180°$, ... for oblate shapes). The energy levels and wave functions of an asymmetric top are determined by solving the collective Schrödinger equation

$$H_{\mathrm{rot}}\Psi_{nJM}(\phi\theta\psi)=E_{nJ}\Psi_{nJM}(\phi\theta\psi), \tag{3.4a}$$

where Ψ_{nJM} is a wave function in the space of the three Euler's angles $(\phi\theta\psi)$ which connect the intrinsic frame axes to the lab frame axes; J denotes the nuclear angular momentum; M is the projection of **J** on the lab$-z$ axis; $n=1,2,3,\ldots$ denote the first (lowest), second, third, ... state with the same J (Π=even for all levels of the model); and the Hamiltonian H_{rot} is given by

$$H_{\mathrm{rot}}=\sum_{k=1}^{3}J_k^2/(2I_k), \tag{3.5}$$

where J_k is the projection of **J** on the intrinsic axis k and I_k is the kth component of the nuclear moment of inertia. (The intrinsic system is defined in such a way that the moment of inertia tensor has only diagonal elements.) Davydov and Filippov (1958) assume[1] that the three moments of inertia are given by

$$I_k=4B\beta^2\sin^2(\gamma-\tfrac{2}{3}\pi k), \tag{3.6}$$

where B is a parameter called the mass parameter. The model Hamiltonian (3.5) depends on 3 parameters: B, β_0, and γ_0 (where β_0, γ_0 are the equilibrium values of β, γ). The Schrödinger Eq. (3.4) is solved in the basis

$$\Psi_{nJM}(\phi\theta\psi)=\sum_K a_{nK}\Phi^J_{MK}(\phi\theta\psi), \tag{3.4b}$$

where Φ is a symmetrized sum of the standard $\mathscr{D}$ functions, K is the projection of **J** on the intrinsic$-z$ axis, and a_{nK} are the mixing coefficients.

In order to calculate the electromagnetic moments, we also need a theory of the electromagnetic operators. In the present version of the collective model [indeed, in all versions of the collective model and in most of the microscopic calculations based on the Nilsson model (Nilsson 1955)] the contributions of the individual nucleons are replaced by a volume integral over *a uniform distribution of electric charges and magnetic moments.*

[1]Equation (3.6) represents the lowest-order terms in β and γ allowed by the rotational invariance of the Hamiltonian. A detailed discussion has been given by Kumar and Baranger (1967).

This electromagnetic density is assumed to be constant inside the nuclear boundaries defined by the relation

$$R(\Omega)=R_0\left[+1\sum_{\mu}\alpha_\mu Y^*_{2\mu}(\Omega)\right] \tag{3.7}$$

[where α_μ ($\mu=-2,\ -1,\ 0,\ 1,\ 2$) denotes the quadrupole deformation tensor in the lab system, and R_0 is the radius of the spherical nucleus] and zero outside. Then, keeping terms to first order in α_μ, one finds that (Bohr and Mottelson, 1953; Davydov and Filippov, 1958)

$$\mathcal{M}(\mathrm{E2},\mu)=\frac{3}{4\pi}ZeR_0^2\alpha_\mu\ , \tag{3.8}$$

$$\mathcal{M}(\mathrm{M1},\mu)=\mu_N g_R\left[\left[\frac{3}{4\pi}\right]^{1/2}J_\mu+\frac{5\sqrt{6}}{7\pi}\sum_{\nu}C^{2}_{\mu-\nu\,\nu\,\mu}\,\alpha^*_{\mu-\nu}J_\nu\right]\ , \tag{3.9}$$

where Z is the nuclear charge, μ_N the nuclear magneton, g_R the nuclear gyromagnetic ratio, **J** the total angular momentum, and C a Clebsch-Gordan coefficient.

Using the wave functions of the rigid rotor model, defined by Eqs. (3.4)—(3.6), and the electromagnetic operators of Eqs. (3.8)—(3.9) (note that in the intrinsic system, $\alpha_0=\beta\cos\gamma$, $\alpha_2=\alpha_{-2}=2^{-1/2}\beta\sin\gamma$, $\alpha_1=\alpha_{-1}=0$), the E2,M1 transition probabilities and the mixing ratios can be obtained. In the case of the $2'\to2$ transition[2] (which is the most relevant one from the point of view of E2,M1 mixing), the reduced transition probabilities are given by

$$B(\mathrm{E2};2'\to2)=\frac{9Z^2e^2R_0^4\beta_0^2\sin^2(3\gamma_0)}{56\pi^2[9-8\sin^2(3\gamma_0)]}\ , \tag{3.10}$$

$$B(\mathrm{M1};2'\to2)=\frac{90\mu_N^2g_R^2\beta_0^2\sin^2(3\gamma_0)}{49\pi^2[9-8\sin^2(3\gamma_0)]}\ , \tag{3.11}$$

and the square of the mixing ratio by

$$\delta^2_{DF}(\mathrm{E2/M1};2'\to2)=\frac{3q^2}{100}\cdot\frac{7}{80}\cdot\left[\frac{ZeR_0^2}{g_R\mu_N}\right]^2\ . \tag{3.12}$$

With $R_0=1.2A^{1/3}$ fm and $g_R=Z/A$, the gyromagnetic ratio for a uniformly charged nucleus (Bohr and Mottelson, 1953), Eq. (3.12) becomes

$$|\,\delta_{DF}(\mathrm{E2/M1};2'\to2)\,|=3.56\times10^{-3}E_\gamma\ (\text{in MeV})A^{5/3}\ . \tag{3.13}$$

In this model, $|\delta|$ is *independent of nuclear shape.* Hence the result is valid for the most asymmetric shape ($\gamma=30°$), as well as for an axially symmetric shape ($\gamma=0°$ or 60°). It is, however, true that the interpretation of the $2'$ state is quite different in the asymmetric rotor model of Davydov and Filippov (1968), and in the axially symmetric rotor model of Bohr and Mottelson (1953). In the former model, two 2^+ states are determined by diagonalizing $H(3.5)$ in a basis of $K=0$ and 2 states: the lower 2^+ state is mostly $K=0$, the upper one is mostly $K=2$. In the later model, the $2'$ state is generally associated with the γ-vibrational band (mostly $K=2$). The Bohr-Mottelson model allows the interpretation of a larger number of observed states. But the interpretation of the $2'$ state is not too different, and the Davydov-Filippov method does predict a useful, parameter-independent estimate for $|\delta|$ (Eq. 3.13).

For comparison with the Weisskopf unit (Sec. III. A), we note that Eq. (3.13) gives for $E_\gamma=1$ MeV, $|\delta_{DF}|=0.17,\ 2.4,\ 7.7,\ 24.4$ for $A=10,\ 50,\ 100,\ 200$, respectively. The experimental values are usually in between the single-particle estimate of Eq. (3.2) and the collective estimate of Eq. (3.13) and indicate the need for including both collective and single-particle aspects in the same model.

Within the approximation of rotation without change of shape, the electric monopole operator of Eq. (2.13b) is just a constant. Hence, only the diagonal matrix elements are nonzero. Thus E0 transitions are not allowed in the extrema limit of rotations without change of shape.

C. Rotation-vibration model

1. The model

In the rotation—vibration model, pioneered by Bohr and Mottelson (1952, 1953, 1975), the low-lying, even-parity states of even-even nuclei are ascribed to the collective quadrupole motion of the nucleus as a whole. The problem can be solved exactly by employing numerical methods (Kumar and Baranger, 1967, Gneuss *et al.*, 1969, Dussel and Bès, 1970). However, from the point of view of understanding and of analyzing experimental data, it is quite useful to consider a perturbation treatment of the problem.

The collective Hamiltonian, appropriate for a perturbation treatment, is written as

$$H_c=H_{\mathrm{rot}}+H_{\mathrm{vib}}+H_{\mathrm{int}}\ , \tag{3.14}$$

where H_{rot} is given by Eq. (3.5),

$$H_{\mathrm{vib}}=V+T_{\mathrm{vib}}\ , \tag{3.15}$$

and

$$H_{\mathrm{int}}=T_{\mathrm{rot}}(\beta,\gamma)-T_{\mathrm{rot}}(\beta_0,\gamma_0)=T_{\mathrm{rot}}(\beta,\gamma)-H_{\mathrm{rot}}\ . \tag{3.16}$$

If the fluctuations about the equilibrium shape (β_0,γ_0) are relatively small, one may obtain a first approximation by neglecting the last term in Eq. (3.14). The motion then separates into rotations and small amplitude vibrations around the equilibrium shape. The corresponding

[2]Since we consider mostly the even parity states in this paper, we shall suppress the superscript + for even parity states.

wave functions can be written as [compare with Eq. (3.4b)]

$$\psi = A_{\rm vib}(\beta-\beta_0,\gamma-\gamma_0)\Phi_{\rm rot}(\phi\theta\psi) \ . \tag{3.17}$$

In higher orders, the interaction $H_{\rm int}$ implies a coupling between rotations and vibrations. This coupling problem has been treated extensively (see the surveys by Davidson, 1965; Davydov, 1967; and Eisenberg and Greiner 1970). A first-order treatment is given in Sec. III C. 2—4.

The basis states of type (3.17) are denoted in the rotation—vibration model by

$$|\, n_\beta n_\gamma JMK\rangle = |\, n_\beta\rangle\, |\, n_\gamma\rangle \Phi^J_{MK}(\phi\theta\psi) \ , \tag{3.18}$$

where n_β equals the number of β phonons and n_γ equals the number of γ phonons. In this model, the equilibrium shape is assumed to be axially symmetric ($\gamma_0=0°$). If the symmetry axis is labeled 3, the moments of inertia of Eqs. (3.5)—(3.6) satisfy the symmetry relations

$$I_1=I_2, \quad I_3=0 \ . \tag{3.19}$$

Additionally, K is a good quantum number for the solutions of the corresponding Hamiltonian.

The low-lying levels can be grouped into rotational bands built on different vibrational states (as in molecular physics). These bands will be denoted in the following by (the allowed values of K,J follow from the symmetry properties of the wave functions)

$$\begin{aligned} &g\text{:}\ \ n_\beta=0, \ \ n_\gamma=0, \ \ K=0 \ \ (J=0,2,4,\ldots) \\ &\beta\text{:}\ \ n_\beta=1, \ \ n_\gamma=0, \ \ K=0 \ \ (J=0,2,4,\ldots) \\ &\gamma\text{:}\ \ n_\beta=0, \ \ n_\gamma=1, \ \ K=2, \ \ (J=2,3,4,\ldots) \end{aligned} \tag{3.20}$$

where g, β, γ refer to ground—state rotational band, β-vibrational band, γ-vibrational band, repspectively.

Before discussing the calculation of E2,M1,E0 matrix elements and the correponding mixing ratios, we consider below a general treatment for any multipole moment. This seems to be necessary, since the order of expansion of the multipole operators has not been given enough attention previously.

2. Perturbation treatment of any multipole moment

Consider a Taylor-series expansion of a multipole operator,

$$\mathscr{M}' = \mathscr{M}_0 + \hat{\alpha}\mathscr{M}_1 + \hat{\alpha}^2\mathscr{M}_2 + 0(\hat{\alpha}^3) \ , \tag{3.21}$$

where $\mathscr{M}_0$ represents the value of the multipole operator corresponding to the equilibrium shape (β_0,γ_0), and $\hat{\alpha}$ represents a deviation from the equilibrium shape, either $(\beta-\beta_0)$ or $(\gamma-\gamma_0)$. Note that $\mathscr{M}_0,\mathscr{M}_1,\mathscr{M}_2,\ldots$ are constants and $\hat{\alpha}$ is an operator with respect to the deformation-dependent wave functions: $|n_\beta\rangle|n_\gamma\rangle$ of Eq. (3.18). Since $\hat{\alpha}$ can be written as a linear combination of a phonon creation and a phonon annihilation operator, the "selection rules" for different terms of the operator expansion (3.21) are

$$\Delta n = 0,1,2,\ldots$$

$$\text{for } \mathscr{M}_0,\hat{\alpha}\mathscr{M}_1,\hat{\alpha}^2\mathscr{M}_2,\ldots, \text{ respectively} \ . \tag{3.22}$$

In Eq. (3.22) and in the following discussion, we have dropped the subscripts β,γ and treated the problem as if it were one dimensional. However, the final results of this section have general validity, since they follow from the general features, such as Eq. (3.22), of vibrational wave functions.

The wave functions for the $n=0,1,2,\ldots$ vibrational states will be coupled by the interaction of type (3.16), which can be expanded in $\hat{\alpha}$. Perturbation theory gives for the modified $n=0,1$ wave functions:

$$\begin{aligned} A'_0(J) &= N_0[A_0(J)+\alpha f(J)A_1(J)+\alpha^2 g(J)A_2(J)+\cdots] \\ A'_1(J_1) &= N_1[-\alpha f(J_1)A_0(J_1)+A_1(J_1) \\ &\quad +\alpha f(J_1)A_2(J)+\cdots] \ , \end{aligned} \tag{3.23}$$

where N_0,N_1 are normalization factors, and $A_n(J)$ is a shorthand notation for the wave functions (3.18). The factors f and g have been introduced so as to take into account the fact that the interaction Hamiltonian (see Eqs. 3.16 and 3.5) depends on J. The mixing coefficient, $\alpha f(J)$, is proportional to $\langle H_{\rm int}\rangle/\Delta E$ as in a perturbation theory. Since both α and $\hat{\alpha}$ arise from the same type of expansion parameter ($\beta-\beta_0$ or $\gamma-\gamma_0$), we consider both to represent the same order. Note that while $\hat{\alpha}$ is an operator, α is a matrix element.

In the case of $n=0\rightarrow n=0$ moments (static if $J_i=J_f$ or transition if $J_i\neq J_f$), the use of "selection rules" (3.22) leads to the following result: the first-order corrections from either the wave function or the multipole operator vanish. Thus the static moments of the g-band levels and the transition moments connecting different levels of the g band are not affected by first-order fluctuations in nuclear shapes.

The same "selection rules" (3.22) yield for the $n=1\rightarrow n=0$ transitions:

$$\begin{aligned} &\langle A'_0(J)\,|\,\mathscr{M}'\,|\,A'_1(J_1)\rangle \\ &\quad = N_0N_1[\langle A_0(J)\,|\,\hat{\alpha}\mathscr{M}_1\,|\,A_1(J_1)\rangle \\ &\qquad +\alpha\{f(J)\langle A_1(J)\,|\,\mathscr{M}_0\,|\,A_1(J_1)\rangle \\ &\qquad -f(J_1)\langle A_0(J)\,|\,\mathscr{M}_0\,|\,A_0(J_1)\rangle\}]+0(\alpha^3) \ . \end{aligned} \tag{3.24}$$

Note that the even-order terms vanish (except for a numerical contribution from the normalization factors). Hence, although the interaction mixes $n=$even and odd states, the even, odd nature of the multipole matrix element is maintained. The electromagnetic moments which corrspond to $\Delta n=$even (odd) in the limit of harmonic vibrations require only even (odd) terms in a perturbative expansion in the vibrational amplitude $(\beta-\beta_0,\ \gamma-\gamma_0)$.

It has been traditional to regard the first term of the right-hand side of Eq. (3.24) as a zeroth-order term and the second term as a first-order term. This terminology

is not correct. However, it is probably not inappropriate to call only the second term a band-mixing term, since the first one comes from the unperturbed wave functions and does not depend on $H_{\rm int}$.

3. First-order treatment of E2/M1, E0/E2 mixing ratios in β- to g-band transitions

In the unperturbed system with no band mixing, the ratio of the B(E2) values depends on the square of the Clebsch-Gordan coefficients in accordance with the Alaga rules (Alaga *et al.*, 1955). The B(M1) values vanish if only the zeroth-order (deformation-independent) part of the M1 operator of Eq. (3.9) is taken into account. This is true for *any* collective wave function, since J is a good quantum number.

The band-mixing treatment has been employed as a powerful tool for analyzing the experimental data, especially the B(E2) values, for a number of years (Nilsson *et al.*, 1961; Mottelson, 1968; Riedinger *et al.*, 1969; and Hamilton, 1972c). A detailed discussion of one of the model versions is given in a recent review article (Kumar, 1975). Hence we shall give here only the main arguments pertaining to E2,M1 mixing ratios.

Consider γ-ray transitions from a β-band level to a g-band level. Since J equals an even integer for the initial and final states, a mixing of E2,M1 multipoles is possible only if $J_i=J_f\geq 2$. E0 transitions are allowed only if $J_i=J_f\geq 0$. It follows from Eq. (3.24) and from the fact that $\mathscr{M}_0$ is just a constant, that the first-order "band-mixing" term vanishes for any multipole. Therefore, we can employ the unperturbed wave functions of the rotation–vibration model.

As regards the first-order part of the electromagnetic operators, two approaches have been employed in the past. (1) Consider an expansion of the nuclear surface such as Eq. (3.7). Assume uniform charge and magnetic moment distributions in the volume bounded by this surface and determine the corresponding electromagnetic moments. The corresponding E2,M1 operators are given by Eqs. (3.8)–(3.9). If we follow the same procedure for the E0 operator of Eq. (2.13), we get to second order in deformation. [Following Rasmussen (1960), the effect of a volume conserving, second-order term in the expansion of the nuclear surface of Eq. (3.7) has been included.]

$$\mathscr{M}(\mathrm{E0})=\tfrac{3}{5}Z[1+\{5/(4\pi)\}\beta^2]\ . \tag{3.25}$$

This is an expansion around the spherical shape ($\beta_0=0$). However, we can convert it into an expansion around the deformed equilibrium shape ($\beta_0,\gamma_0=0°$) by replacing β by $\beta_0+(\beta-\beta_0)$. (2) The second approach is to make a Taylor-series expansion of the operator around its equilibrium value (Mottelson, 1968; Kumar, 1975).

The second approach appears to be more consistent with the idea of expanding the collective Hamiltonian around the equilibrium shape. However, at least to first order, the two approaches differ only in the parametrization of the absolute values of electromagnetic moments or mixing ratios. Both predict the same angular momentum dependence for the mixing ratios, since the derivatives of the operators needed for a Taylor-series expansion are independent of J.

Calculation of the E2,M1 moments in the intrinsic (β,γ) system requires the transformation of the E2,M1 operators of Eqs. (3.8) and (3.9) to the intrinsic system. Then the E2(M1) operator is a sum of products of intrinsic operators and $\mathscr{D}$ functions. The Φ part of Eq. (3.18) is a symmetrized sum of $\mathscr{D}$ functions. After integrating out the $\mathscr{D}$ functions, the E2 matrix element for a $J_\beta\rightarrow J$ $(=J_g)$ transition can be written as

$$\langle J\,||\,\mathscr{M}(\mathrm{E2})\,||\,J_\beta\rangle=Y[(2J_\beta+1)]^{1/2}C^{J_\beta 2J}_{0\,00}\times\langle n_\beta=0\,|\,\beta-\beta_0\,|\,n_\beta=1\rangle\ , \tag{3.26}$$

where

$$Y=3(4\pi)^{-1}ZeR_0^2\ . \tag{3.27}$$

A similar procedure for the E0 transitions gives

$$\rho(\mathrm{E0};J_\beta\rightarrow J)=3Z(2\pi)^{-1}\times\langle n_\beta=0\,|\,\beta-\beta_0\,|\,n_\beta=1\rangle\beta_0\ . \tag{3.28}$$

Substitution of Eqs. (3.26–3.28) into Eq. (2.15) gives

$$\varepsilon(\mathrm{E0/E2};J_\beta\rightarrow J)=-2\beta_0[C^{J2J}_{000}]^{-1}=2\beta_0\left[\frac{(2J-1)(2J+3)}{J(J+1)}\right]^{1/2}\ . \tag{3.29}$$

The usual X value, defined by Rasmussen (1960), equals ε^2. The q value has the same sign as ε, which is predicted to be positive (negative) for prolate (oblate) nuclei and can be obtained by employing Eq. (2.14).

Equation (3.29) is strictly valid only for $J>0$. However, a useful strength parameter or a branching ratio for the decay of a 0_β state can be defined as (note that the band-mixing contribution to the E2 matrix element is comparatively small and has been neglected here)

$$\varepsilon(\mathrm{E0};0_\beta\rightarrow 0/\mathrm{E2};0_\beta\rightarrow 2)=2\beta_0\ . \tag{3.30}$$

The above results have been obtained by employing procedure (1). If procedure (2) had been employed, the E0,E2 operators would have required one parameter each for the Taylor-series expansion. Then the expressions in Eqs. (3.29) and (3.30) would have been multiplied by one unknown parameter. Therefore the absolute values of the mixing ratios predicted by Eqs. (3.29) and (3.30) depend on the assumption of uniform charge distribution employed in procedure (1). But the angular momentum dependence of the mixing ratios is independent of this assumption and is likely to have greater validity.

In the case of the M1 operator, it is more convenient to employ procedure (2). Instead of the relation (3.9), the

M1 operator is written as

$$\mathcal{M}(\mathrm{M1},\mu)=\mu_N\left[\frac{3}{4\pi}\right]^{1/2}\sum_\nu \mathscr{D}^1_{\mu\nu}g_\nu(\beta,\gamma)J_\nu\ , \qquad (3.31)$$

where g_ν is the gyromagnetic ratio vector defined in the intrinsic system. If the deformation dependence and the vectorial nature of g_ν are neglected, then Eq. (3.31) reduces to the first term of Eq. (3.9). General relations for calculating M1 moments by using the operator (3.31) have been given previously (Kumar and Baranger, 1967). From these relations, it is observed that in the case of β-band ($K=0$) to g-band ($K=0$) transitions, only the following Taylor-series expansion is needed:

$$g_+=\tfrac{1}{2}(g_1+g_2)=g_0+(\partial g_+/\partial\beta)_0(\beta-\beta_0)\ , \qquad (3.32)$$

where the subscripts 1, 2 refer to the intrinsic axes, and g_0 is the equilibrium value. With the unperturbed wave functions (3.18), the M1 matrix element for a $J_\beta\to J$ ($=J_g$) transition is given by ($J_\beta=J>0$)

$$\langle J\,||\,\mathcal{M}(\mathrm{M1})\,||\,J_\beta\rangle = -[3J(J+1)(2J+1)/(4\pi)]^{1/2}(\partial g_+/\partial\beta)_0 \times\langle n_\beta=0\,|\,\beta-\beta_0\,|\,n_\beta=1\rangle\ . \qquad (3.33)$$

The combination of Eqs. (2.6), (3.26), and (3.33) gives $J_\beta=J>0$

$$\delta(\mathrm{E2/M1};J_\beta\to J) =0.835(3/4\pi)^{1/2}F(J,J_\beta)ZR_0^2\ (\text{in b}) \times E_\gamma\ (\text{in MeV})/[(\partial g_+/\partial\beta)_0\ \text{in nm}]\ , \qquad (3.34a)$$

where

$$F(J,J_\beta)=[(2J-1)(2J+3)]^{-1/2}(J_\beta=J)\ . \qquad (3.34b)$$

The parameter $(\partial g_+/\partial\beta)_0$ is in general not known. But Eq. (3.34) can be employed to test the angular momentum dependence of the E2/M1 mixing ratios in β-band to g-band transitions. The same angular momentum dependence has been obtained by Grechukhin (1969), who employed an expansion of type (3.9) except for multiplying the α-dependent term by an arbitrary factor.

Ejiri and Hagemann (1971) analyzed their experimental data for ^{154}Gd and ^{174}Hf in terms of Eq. (3.34) and found deviations from the first-order treatment. One could attempt to extend the above analysis to higher-order terms of the perturbation theory, but we shall not do so, because exact methods are now available (see Sec. III. D. 2) which allow for the mixing of rotations, β vibrations, and γ vibrations to all orders.

Microscopic calculations (Kumar, 1975) of $g_+(\beta,\gamma)$ show that it is a complicated function of nuclear shape. In the case of ^{152}Sm, the calculated function g_+ has a *local maximum* at $\beta=\beta_0$, $\gamma=\gamma_0$. Therefore the derivative $(\partial g_+/\partial\beta)_0$ vanishes. Hence the calculated M1 matrix elements (which are small but nonzero) come from the second- and higher-order terms. We do not know if this is a general feature of deformed nuclei. But it should serve as a warning that one should not be surprised to find deviations from the first-order treatment discussed above.

4. First-order treatment of E2/M1, E0/E2 mixing ratios in γ- to g-band transitions

This treatment is analogous to that of Sec. III. C. 3 except for some extra complications related to the fact that $I=$odd values are allowed for the γ band ($K=2$). Hence E2/M1 mixing ratios can occur in transitions for which $\Delta J=1$, 0, and we must consider "band-mixing" terms coming from the second term of Eq. (3.24). For this purpose, the interaction term of Eq. (3.16) is needed. A Taylor-series expansion of the moments of inertia to first order in γ (remember that $\gamma_0=0°$) gives

$$I_1=I_0+\left[\frac{\partial I}{\partial\gamma}\right]_0\gamma\ ,$$
$$I_2=I_0-\left[\frac{\partial I}{\partial\gamma}\right]_0\gamma\ ,\quad I_3=0+0(\gamma^2)\ , \qquad (3.35)$$

where we have employed the invariance properties of the collective Hamiltonian (Bohr, 1952; Kumar and Baranger, 1967; Bohr and Mottelson 1975). The expansion (3.35) is substituted into the interaction Hamiltonian and the resultant mixing of γ-, g-band levels (with the same J) is determined via perturbation theory. The final expression for the E2 matrix element for a $J_\gamma\to J$ transition is

$$\langle J\,||\,\mathcal{M}(\mathrm{E2})\,||\,J_\gamma\rangle=Y\beta_0(2J_\gamma+1)^{1/2}C^{J_\gamma 2J}_{2\,-20}\langle n_\gamma=0\,|\,\gamma\,|\,n_\gamma=1\rangle[1+\tfrac{1}{2}Z_2\{J(J+1)-J_\gamma(J_\gamma+1)+4\}]\ , \qquad (3.36)$$

where

$$Z_2=\sqrt{3}(\partial I/\partial\gamma)_0[(\hbar\omega_\gamma)I_0^2]^{-1}\ , \qquad (3.37)$$

Y is given by Eq. (3.27), and $\hbar\omega_\gamma$ is the energy of a γ vibrational phonon (Kumar, 1975). The band-mixing parameter, Z_2, is usually determined from the slope of the straight line [predicted by Eq. (3.36)] which gives the best fit to the available data.

Since the zeroth-order part of the M1 operator is a constant times **J**, it gives a zero contribution to M1 transitions. Hence we need to consider only the first term of Eq. (3.24) which requires unperturbed wave functions and the

first—order part of the M1 operator. From the general expression for M1 matrix elements (Kumar, 1975), it can be seen that we need only the combination $g_-=\frac{1}{2}(g_1-g_2)$ for $\Delta K=2$ transitions.[3] A Taylor-series expansion of g_- gives

$$g_-=0+\left[\frac{\partial g_-}{\partial\gamma}\right]_0\gamma\,. \tag{3.38}$$

The zeroth part of g_- vanishes because of axial symmetry. The M1 matrix element for a $J_\gamma\to J$ $(=J_g)$ transition is given by

$$\langle J\,||\mathscr{M}(\mathrm{M1})||\,J_\gamma\rangle=(-1)^{(J_\gamma-1)}C^{J\,1\,J_\gamma}_{0\,1\,1}[3(2J+1)(J_\gamma-1)(J_\gamma+2)/(16\pi)]^{1/2}$$
$$\times(\partial g_-/\partial\gamma)_0\langle n_\gamma=0\,|\,\gamma\,|\,n_\gamma=1\rangle\ \text{(Kumar, 1975)}\,. \tag{3.39}$$

On substituting Eqs. (3.36) and (3.39) into Eq. (2.6), we find the δ-value for a $J_\gamma\to J$ transition to be

$$\delta(\mathrm{E2/M1};J_\gamma\to J)=0.835E_\gamma\ (\text{in MeV})[32\pi B(\mathrm{E2};0\to2)\ \text{in}\ e^2\times\mathrm{b}^2]^{1/2}F(J,J_\gamma)[\partial g_-/\partial\gamma)_0\ \text{in nm/rad}]^{-1}\,, \tag{3.40}$$

where

$$F(J,J_\gamma)=[1+\tfrac{1}{2}Z_2\{J(J+1)-J_\gamma(J_\gamma+1)+4\}]/[(J+J_\gamma-1)(J+J_\gamma+3)(J-J_\gamma+2)(J_\gamma-J+2)]^{1/2}\,. \tag{3.41}$$

The same angular momentum dependence of δ, except for the Z_2-dependent term, has been obtained by Grechukhin (1969).

To the order considered here, E0 transitions are not allowed between a γ-band level and a g-band level. Hence ε(E0/E2) equals zero (when E2 is allowed) for such transitions.

Alternative methods of deriving relations of type (3.34) and (3.40) have been discussed by Greiner (1966). Second-order terms have been given by Lange (1970) (see Sec. V.B). Greiner has also given a relation for δ(E2/M1; 2′→2), where the 2,2′ states are described as the $N=1,2$ phonon states of the vibrational model (harmonic, quadrupole vibrations around the spherical shape). However, the experimental measurements of spectroscopic quadrupole moments (de Boer and Eichler, 1968) have shown that the applicability of the vibrational model is quite limited. Near closed shells, couplings with the particle-hole (quasiparticle) excitations become important. Away from closed shells, anharmonicities due to deviations from the spherical shape increase rapidly. The perturbaion treatment based on the rotation—vibration model discussed above is expected to work best for well-deformed nuclei. However, it provides a useful method for analyzing the E2,M1,E0 mixing ratios of any nucleus, since most of the geometrical factors—such as Clebsch-Gordan coefficients—are taken out.

Another approach has recently been developed by Maruhn-Rezwani *et al.* (1975). They make perturbation expansions of the collective Hamiltonian and the E2,M1 operators in different powers of the quadrupole deformation tensors. The collective operators have nonvanishing matrix elements only between different magnetic substates of a given nuclear state, unless the gyromagnetic ratio g (the ratio of the moment of inertia of the charged particles to that of the total nucleus) depend on intrinsic variables such as the quadrupole deformation. Such a dependence of the g factors on nuclear deformation results quite naturally in a recently developed generalization of the collective model (Maruhn-Rezwani *et al.*, 1975; Baker *et al.*, 1975) which allows for independent quadrupole deformations tensors $\alpha_p^{[2]}$ and $\alpha_n^{[2]}$ for protons and neutrons. It is advantageous to introduce an average deformation $\alpha^{[2]}=(B_p\alpha_p^{[2]}+B_n\alpha_n^{[2]})/B$ and a deviation tensor $\xi^{[2]}=\alpha_n^{[2]}-\alpha_p^{[2]}$, where B_p and B_n are the mass parameters for protons and neutrons and $B=B_p+B_n$.

The Hamiltonian may be set up as $H=H(\alpha)+H(\xi)+H(\alpha,\xi)$, where $H(\alpha)$ is the Hamiltonian obtained in the prescription of Gneuss and Greiner (1971). The strong coupling between α_p and α_n allows one to use the harmonic oscillator approximation for $H(\xi)$ with a level spacing of the order of the energy of the giant dipole resonance. The interaction potential $V(\alpha,\xi)$ is to lowest order given by $V(\alpha,\xi)=C[\alpha\times\xi]^{[0]}+D([\alpha\times\alpha]\times\xi)^{[0]}$, with C and D as yet unknown constants to be determined from experiment.

If spin effects are neglected, the magnetic moment operator in this model is simply the orbital angular momentum of the protons, which does not commute with the total Hamiltonian. However, if the interaction $V(\alpha,\xi)$ is treated in perturbation theory, the M1 matrix elements may be expressed as matrix elements of an effective operator

$$\mathrm{M1}_{\mathrm{eff}}=i\sqrt{10}\left[\frac{B_p}{B}+C_1'\frac{B_nB_p}{2B^2}\right][\alpha\times\pi]^1$$
$$+iC_2'\frac{5}{2}\frac{B_nB_p}{B^2}[[\alpha\times\alpha]^2\times\pi^2]^1 \tag{3.42}$$

[3]The M1 operator can in general connect states with $\Delta K=2$, since the angular momentum part of the operator can change K by one unit and since the $\mathscr{D}$-function part of the operator can change K by one additional unit.

between the unperturbed eigenstates of $H(\alpha)$ alone. Clearly, this effective M1 operator contains a deformation dependent g factor and is not in general parallel to the angular momentum operator.

The E2 operator is also modified by the presence of the ξ degree of freedom in an effective E2 operator

$$\mathrm{E2}_{\mathrm{eff}}=\rho_0 R_0^5\left[\left[1+C_1'\frac{B_n}{2B}\right]\alpha^2 - \left[\frac{10}{\sqrt{70\pi}}-C_2'\frac{B_n}{2B}+C_2'\frac{10}{\sqrt{70\pi}}\frac{B_n}{B}\right]\times[\alpha^2\times\alpha^2]^2\right]. \tag{3.43}$$

By using Eqs. (3.42), (3.43), and (2.5), we can now evaluate the δ values and determine the unknown quantities C_1' and C_2' from a least-squares fit to the experimental data, as discussed later.

This approach has yielded good agreement with the experimental δ(E2/M1) values of ^{186,188,190,192}Os and ^{192}Pt (Maruhn-Rezwani *et al.*, 1975) and ^{166}Er (Baker *et al.*, 1975). However, the number of parameters is considered larger than in the rotational model including first-order band mixing. Hence further tests of the model are needed.

D. Microscopic models

Although a large number of microscopic models have been developed during recent years, only a few have been employed for the calculation of the mixing ratios. One of these is the convention shell model, where the problem of a few particles moving in a given configuration space is solved exactly. Such calculations have been performed by Halbert *et al.* (1971) for $A=18-22$ with $2-10$ active nucleons moving in $s-d$ shells. The same model has been applied by Glaudemans and Wildenthal (1971) to explain the E2/M1 mixing ratios in $s-d$ shell nuclei. However, such methods are still too complicated for heavy nuclei. Since the present review concerns mostly the heavy nuclei, we describe below only those three methods which have been employed for heavy nuclei.

Two of these three methods employ the same model for residual nucleon-nucleon interactions: the pairing-plus-quadrupole (PPQ) model. This model has been used widely during the past 20 years to include both the individual-particle and collective aspects of nuclei in a systematic calculation for all nuclei with just the pairing- and quadrupole-strength parameters [for recent reviews, see Bès and Sorensen (1969) and Kumar (1975)].

1. Volume conservation plus quasiboson method

Bès (1963) has developed and employed this method to calculate the strength parameter, X(E0/E2), for the decay of the 0_β state. Bès *et al.* (1965) have employed the same method to calculate δ^2(E2/M1; $2_\gamma\rightarrow 2$). Both calculations have been performed for deformed nuclei with $A=150-190$, $226-256$.

Briefly, the main steps of the calculation are the following. (1) Nilsson levels, corresponding to the experimental value of equilibrium deformation, are employed as the single-particle basis. These levels depend on a prescription for imposing volume conservation. Hence the method is called a "volume conservation" method as opposed to a "self-consistent" method. (2) A Bogolyubov transfomation from particle, hole states to quasiparticle states is performed, i.e., the u,v factors are calculated. The pairing strength parameters (one for protons, one for neutrons) are chosen so as to fit the experimental odd-even mass differences. (3) The PPQ model Hamiltonian is expressed in the deformed, quasiparticle basis defined by steps (1) and (2). (4) The residual nucleon-nucleon interaction in the new basis is treated in the quasiboson approximation. The assumption of small amplitude, harmonic vibrations in β (or γ) is employed. The method is similar to the random-phase-approximation (RPA) method used for describing a strongly collective state of a spherical nucleus. Since the β- (γ-) vibrational states of deformed nuclei are not very collective (the E2 transition strength for the decay of such a vibrational state to the ground state is only a few Weisskopf units), there is some question about the applicability of an RPA method to the present problem.

The predicted (Bès, 1963) X(E0/E2) values for the decay of 0_β states are too large compared to experiment by a factor ranging from 2 to 10. The predicted δ^2(E2/M1) values (Bès *et al.*, 1965) are in general too small compared to experiment by an order of magnitude.

A better agreement with the experimental X(E0/E2) values for the decay of 0_β states has been obtained by Silvestre-Brac and Piepenbring (1973), who have developed an improved version of the quasiboson (RPA) method. According to their calculations, the X value does not distinguish between a collective $0'^+$ state and a two-quasiparticle $0'^+$ state, but it is larger for proton excitations as compared to neutron excitations by a factor of $15-30$. These calculations are, however, limited to 0^+ states only.

A large number of ρ(E0) values for the $A=150-190$ region have been calculated by Birbrair *et al.* (1975), who have combined the Migdal theory with the volume conservation method.

2. Self-consistent, time-dependent Hartree-Bogolyubov method (pairing-plus-quadrupole model)

This method has been developed by Kumar and Baranger [Kumar (1975); see also references cited there]. It is not a fully self-consistent method, since the spherical single-particle energies are not derived self-consistently from a nuclear force. But is is self-consistent in the sense that the potential deformation

equals the wave-function deformation. Furthermore, nuclear deformation is not assumed *a priori* as in the Nilsson model. It arises from the quadrupole force.

A more important distinction from the volume-conservation—plus-quasiboson method discussed above is in the method of calculation of the collective states, as discussed below. The main steps of the calculation are the following.

(1) The deformed single-particle levels and wave functions are calculated by diagonalizing (in a spherical basis) the Hamiltonian

$$H_D = H_S - \sum_M \beta_{2M} Q_{2M} , \tag{3.44}$$

where

$$\beta_{2M} = \chi \langle Q_{2m} \rangle , \tag{3.45}$$

H_S is the spherical part of the average field, Q_{2m} is a quadrupole operator, and χ is the strength of the quadrupole force.

(2) The deformed quasiparticle states are calculated by performing a Bogolyubov transformation. The mixing amplitudes of this transformation (u,v factors) depend on two pairing strength constants; one for protons and one for neutrons.

(3) A straightforward minimization of the expectation value of the two-body Hamiltonian (the PPQ model Hamiltonian has been employed in previous calculations), with respect to a Slater determinant built on the deformed quasiparticle states, would give the ground-state equilibrium shapes (β_0,γ_0 of the rotational model). However, in order to calculate the properties of the excited states and the mixing ratios in electromagnetic transitions, a theory of the excited states is needed. For this purpose, a time-dependent theory is employed where the Slater determinant (or nucleon density) depends not only on β_{2M} but also on its time-derivatives, $\dot{\beta}_{2M}$. The expectation value of the two-body Hamiltonian is taken with respect to such a time-dependent Slater determinant. Terms up to second order in the time derivatives are kept (the adiabatic assumption is made), and the resulting energy expression is cast in the form of the collective Hamiltonian of Eq. (3.14). This step may be regarded as a projection from the $3A$-dimensional space of a microscopic Hamiltonian to the five-dimensional space of a collective Hamiltonian for quadrupole motion.

(4) The collective Hamiltonian, a generalized form of Eq. (3.14), since an expansion around (β_0,γ_0) is *not* made, is initially a classical Hamiltonian depending on velocities ($\dot{\beta}_{2M}$). This Hamiltonian is quantized and a collective Schrödinger equation in the five quadrupole variables is constructed. This equation is solved by means of numerical approximation methods (Kumar and Baranger, 1967). Coupling between vibrations and rotations, including K mixing, is taken into account exactly. However, the microscopic calculation of the potential and inertial functions, which enter the collective Hamiltonian, involves the following approximations: (a) PPQ interaction, (b) oscillator wave functions are used for the radial part of the basis wave functions, (c) Coriolis antipairing or decrease of pairing effects with angular momentum is neglected, and (d) direct coupling to two or more quasiparticle states is neglected.

3. Dynamic deformation model

A practical limitation of the PPQ model arises from the shell-model-type division of the nucleus into an inert core and a cloud of valence nucleons. This is not simply a computational limitation but a more fundamental limitation of the PPQ model, since the PPQ interaction gives too much configuration mixing if it is allowed to operate in a configuration space larger than two oscillator shells.

In spite of this limitation, the PPQ model of Kumar and Baranger was extremely successful because it went far beyond the usual theories of nuclear deformation. This is because, instead of employing the classical approximation of a nucleus with a fixed shape (corresponding to the minimum of the potential energy of deformation), Kumar and Baranger solved the collective Schrödinger equation depending not only on the potential energy but also on the kinetic energy of deformation. This required the treatment of nonaxial deformations on the same footing as the axial ones and the calculation of seven functions of deformation: potential energy; three rotational moments of inertia; and three mass parameters for $\beta\beta$, $\beta\gamma$, $\gamma\gamma$ vibrations.

The dynamic deformation model (Kumar, 1980, 1981) combines the dynamic treatment of nuclear deformations outlined above with a better microscopic theory, where the PPQ model is replaced by the Nilsson-Strutinsky method. Deformations arise in the single-particle model simply because the average field has three frequencies of oscillation ($\omega_x,\omega_y,\omega_z$). These three are equivalent to ω_0 (fixed by the nuclear size), β, and γ. The last two are treated as dynamic variables. Hill-Wheeler relations between the ellipsoidal axis lengths and β,γ are employed so that (a) volume conservation is satisfied exactly at all deformations, and (b) a multipole expansion of the nuclear surface contains not only quadrupole ($\lambda=2$) deformations but also hexadecapole ($\lambda=4$) and smaller amounts of higher multipoles.

A large configuration space ($N=0-8$ shells) is employed. Complete mixings of type $\Delta N=2$, $\Delta l=2$, $\Delta j=1$ or 2, $\Delta m=2$ are taken into account for a large number of (β,γ) sets. If such a calculation had to be repeated for each nucleus, it would be a formidable computational task. Hence a scaling method has been developed so that the same single-particle levels and matrix elements (multiplied by approximate scaling factors) can be employed for all nuclei. Of course, some drastic assumptions had to be made about the spherical single-particle energies. Still, it was possible to show that the general features of the low-energy spectra of practically all even-even nuclei [rotational energies, vibrational band head, B(E2) values, quadrupole moments, magnetic moments] could be reproduced *without any fitting parameters.* Furthermore,

the same model has been employed for a large variety of nuclear phenomena: nuclear structure, fission, neutron cross sections, and giant resonances.

E. Interacting boson model

The interacting boson model (IBM) (Arima and Iachello, 1975, 1976); Iachello, 1980; Casten, 1980) has enjoyed considerable success in recent years. In this model, the low-energy states of even-even nuclei are described in terms of interactions between s ($J=0$) and d ($J=2$) bosons. The corresponding Hamiltonian is diagonalized in this boson space by employing some rather powerful and efficient group theory methods.

While there is general agreement that this is a good method of solving the collective Hamiltonian, there is no general agreement about the meaning of the s and d bosons.

One point of view is that this is another way of writing the quasiboson Hamiltonian, where one expands products of two fermion operators in terms of quadrupole bosons. In particular, Paar (1980) has shown that the Schwinger representation of such a Hamiltonian leads to the SU(6) Hamiltonian, the most general form of the IBM. However, the IBM works better (and faster) than most quasiboson methods. This may be because the different matrix elements are not calculated microscopically, but fitted to experiment for each major shell. This may be a practical way of including many-fermion correlations.

Two of the recent versions of the IBM are called IBA-1 and IBA-2. The version IBA-1 refers, in principle, to a microscopically derived version of the IBM. However, the IBA-1 employed in most of the comparisons with experiments (Casten, 1980) is identical to the IBM, since the model parameters are determined by a direct fit to some of the data rather than being deduced microscopically. The version IBA-2 includes four types of bosons: one set of (s,d) for neutrons and a second set for protons.

An interesting aspect of the IBM, from the point of view of the present review of the mixing ratios, is the treatment of the M1 operator which is written as (Arima and Iachello, 1976).

$$T_k^{(\mathrm{M1})}=m_1(d^\dagger d)_k^{(1)}+\tilde{m}_1'[(d^\dagger s)^{(2)}(d^\dagger d)^{(1)} +(d^\dagger d)^{(1)}(d^\dagger s)^{(2)}]_k^{(1)} .$$

The first term of this operator, the m_1 term, is proportional to the angular momentum operator. Hence it gives no M1 transitions (which is the same as in the collective model discussed above in Sec. III.C). The M1 transition matrix elements come entirely from the second term. Hence they are proportional to a single constant, $\tilde{m}_1'$. In the pure vibrational limit, the E2 matrix elements are also proportional to a single constant. Hence, in this limit, the mixing ratios $\delta(\mathrm{E2/M1})$ are proportional to a single constant (D) and are given by

$$\delta(\mathrm{E2/M1})=DE_\gamma\Delta^{(\mathrm{E2/M1})} ,$$

where E_γ is the transition energy and $\Delta^{(\mathrm{E2/M1})}$ is essentially a geometrical factor depending on the angular momentum of the initial and the final states. This factor can be found in Table IX of Arima and Iachello (1976) for a number of transitions allowed in the vibrational limit.

Scholten, Iachello, and Arima (1978) have extended the above to deformed nuclei and have shown that a similar relation applies to the $\Delta I=1$ transitions, which leads to the general result

$$\frac{\Delta(I\to I+1)}{\Delta(I\to I-1)}=\left[\frac{(I-1)(I+1)}{I(I+2)}\right]^{1/2} ,$$

which is exactly the same as that predicted by the band-mixing model (see Sec. III.C.4) for $\gamma\to g$ transitions (assuming the mixing parameter for E2 transitions, Z_2, to be zero). Comparison with the experimental data of Table IVa shows that this relation agrees with experiment within a factor of 2 or within experimental errors (which are quite large in many cases).

The IBA goes beyond the conventional collective model of Bohr and Mottelson in that simple analytical relations spanning the entire vibration–rotation region are given and in that parameters are determined for each major shell rather than for each nucleus. However, it remains to be seen whether the IBM can be made as parameter independent and as general as the microscopic version of the collective model, the dynamic deformation model (see the brief discussion in Sec. III.D).

F. The meaning of the signs of the mixing ratios

The sign of the E2/M1 mixing ratio [Eqs. (2.5) and (2.6)] equals the relative sign of the E2, M1 transition moments. Can we relate it to the sign of the nuclear quadrupole moment or deformation? In the limit of rigid rotations without change of shape [Eqs. (3.12) and (3.13)], the δ value for a $2'\to 2$ transition is independent of nuclear shape. In the first-order perturbation treatment of deviations from the equilibrium shape, the sign of the δ value equals the sign of $(\partial g_+/\partial\beta)_0$ in the case of a $\beta\to g$ transition [Eq. (3.34)] or the sign of $(\partial g_-/\partial\gamma)_0$ in the case of a $\gamma\to g$ transition [Eq. (3.40)]. To the order considered, the intrinsic quadrupole moment Q_μ is proportional to deformation β_μ ($Q_0\sim\beta$, $Q_2\sim\beta_2\sim\beta\gamma$). Hence we can combine the two results as

$$\text{sign of } \delta(\mathrm{E2/M1})=\text{sign of } (\partial Q_\mu/\partial g_\nu)_0 , \qquad (3.46)$$

where $\mu=0$, $\nu=+$ for a $\Delta K=0(\beta\to g)$ transition, $\mu=2$, $\nu=-$ for a $\Delta K=2(\gamma\to g)$ transition, and the subscript 0 implies that the derivative is to be evaluated at the equilibrium shape. Although the result (3.43) has been derived by using the approximation of small-amplitude vibrations around a well-deformed shape, the result is somewhat more general, since it depends only on the

purity of the K-quantum number. This purity depends not only on the softness against γ vibrations, as measured by the energy ratio E_{2_γ}/E_2 and the splitting $E_{2_\gamma}-E_4$ (Kumar, 1970), but also on the splitting $E_{2_\beta}-E_{2_\gamma}$. Previous calculations of the type discussed in Sec. III. D. 2 give a K mixing of only about 20% for two of the γ softest (most asymmetric in Davydov-Filippov language) nuclei, ^{190}Os and ^{192}Os, but a K mixing of about 50% for ^{182}W (Kumar and Baranger, 1968) and for ^{150}Sm (Kumar, 1974).

Microscopic calculations based on the pairing-plus-quadrupole model (Kumar and Baranger, 1968; Kumar, 1969) show that the so-called "spin contribution" to the nuclear gyromagnetic ratio is $\pm 15\%$. Although this is a comparatively minor contribution to the diagonal M1 matrix elements, the magnetic moments, it is extremely important for the B(M1) values and the δ(E2/M1) values which do not depend on the constant (deformation-independent) part of the g values (Kumar, 1969). It may be fruitful to study the spin contributions in greater detail in future calculations.

The first-order treatment does not allow E0/E2 mixing in $\gamma \rightarrow g$ transitions. But the prediction for the $\beta \rightarrow g$ transitions is [Eq. (3.29)]

$$\text{sign of } \varepsilon(\text{E0/E2}) = \text{sign of } \beta_0 \,, \tag{3.47}$$

where β_0, the equilibrium value of nuclear deformation, is positive (negative) for a prolate (oblate) nucleus. The microscopic calculations, which include many higher-order terms and which allow for E0/E2 mixing in $\gamma \rightarrow g$ transitions, show that the relation (3.47) is also valid for $\gamma \rightarrow g$ transitions [see Table 3.2 in Kumar (1975)]. The systematics and the accuracy of the experimentally determined signs of ε values are not very good at present. Further improvements in the experimental technique of electron-γ angular correlations would be quite valuable for testing the validity of Eq. (3.47).

The above discussion of the mixing ratios has been given mostly in the collective model language of deformations, rotations, vibrations, etc. However, it should be pointed out that a completely equivalent description can be given in terms of the configuration mixing language of the shell model. As already pointed out (Sec. III. D), the conventional shell-model calculations have been quite successful in describing the light nuclei (whose spectra also show many "collective" features). It seems to us that the two methods should supplement rather than compete with each other. A shell-model calculation may be performed whenever technically feasible, but the collective model language is usually more useful from the point of view of understanding. However, one has to be careful while attempting to combine in a direct way the collective model and shell-model wave functions (languages). A collective wave function is a shortcut (often incomplete but still very useful) method of writing a very complicated mixture of different types of nucleon configurations. Hence it is usually *not orthogonal* to a few-nucleon wave function. Since this orthogonality is usually not taken into account in the core- (vibrator or rotator) particle coupling models, there is a danger of Pauli principle violation. Many theorists are now engaged in finding suitable solutions to this problem. But these developments are beyond the scope of the present paper. Hence we have not discussed such models. But for the sake of completeness, we mention that an interpretation of the sign of the E2/M1 mixing ratio, based on a core-particle coupling model, has been given by Tamura and Yoshida (1962).

IV. EXPERIMENTAL RESULTS FOR E2/M1 AND E0/E2 MIXING RATIOS

A. Procedures and results for E2/M1 mixing ratios

1. General procedures and format of the table

Table I provides averaged data on the magnitude and sign of the E2/M1-mixing ratios of nuclear transitions which were obtained from a careful review of all γ-angular correlations and γ-distribution and γ-linear polarization measurements. While internal coefficients cannot provide the signs of δ or accurate δ values in general, in a few cases ICC information could be used to remove ambiguities. Accurate subshell ratios, however, can yield accurate magnitudes of δ and a few are included. The data have been surveyed up to January 1980.

The transitions of interest here are those between states of the low-energy quadrupole excitation modes of even-even nuclei. This restricts the data to be compiled to states whose energies are comparable to that of the pairing gap for two-quasiparticle excitations. When information on a series of states is available, as in some cases of low and medium A nuclei, we list the states only up to the energy of the fourth 2^+ level, i.e., in our notation up to $2'''$.

The table gives in the first column the nucleus and next the energy of the state and that of the depopulating transition where δ is being reported in keV. Only those transitions are given which proceed between levels for which the angular momentum and positive parity are established, and these quantum numbers are given in the next column. For vibrational nuclei, the sequence of levels is indicated by primes as given above, while for rotational states we also quote the K-quantum numbers, e.g., I, $K-I_g$ to distinguish between the ground band and other $K=0$ states. The remaining three columns give the mixing ratios in the sign convention of Krane and Steffen (1970) and the method of the determination and the reference according to the Nuclear Data Keywords. A reference not repeated in the next or following lines denotes the same authors as the last one listed. The experimental methods are divided into two major groups denoted by R for investigations which use radioactive sources and A for in-beam work at accelerators. They are further characterized by G for $\gamma\gamma$-angular correlations, P for particle-γ-angular correlations, and D for γ-

TABLE I. Data and adopted values for E2/M1 mixing ratios.

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
$^{16}_{6}C_{10}$	3980/2210	2′−2	−0.18(15)	AP0	Balamuth *et al.* (1977)
	4080/2320	3−2	−0.10(9)		
$^{18}_{8}O_{10}$	3921/1939	2′−2	−0.10(10)	AP0	Litherland *et al.* (1961)
			−0.18(10)	AP0	Ollerhead *et al.* (1965)
			−0.08(5)	AP0	Berant *et al.* (1971)
			−0.19(8)	AP0	Becker *et al.* (1973)
			−0.12(4)		
	5260/3278	2″−2	−0.2(1)	AP0	Lopes *et al.* (1966)
			−0.14(4)	AP0	Berant *et al.* (1971)
			−0.15(4)		
	5378/3396	3−2	0.00(5)	AP0	Lopes *et al.* (1966)
$^{18}_{10}Ne_{8}$	3616/1729	2′−2	$0.1 \leq \delta < 1.4$	AD1	Robertson *et al.* (1969)
			0.9(7)	AP0,AP1	Rolfs *et al.* (1969)
			−0.09(7)	AP0	Shapiro *et al.* (1970)
			−0.03(9)	AP1	Glavish *et al.* (1972)
			−0.06(6)		
			$8.4^{+1.5}_{-1.0}$	AD1	Alexander *et al.* (1972)
$^{20}_{10}Ne_{10}$	7421/5787	2′−2			
			0.06(4)	AP0	Pelte *et al.* (1964)
$^{22}_{10}Ne_{12}$	4457/3182	2′−2	0.11(3)	AP0	Broude and Eswaran (1964)
			0.08(2)	AP0	Buhl *et al.* (1967)
			0.08(2)	AP0	Kutschera *et al.* (1968)
			0.083(12)		
			−0.25(8)	AP0	Kutschera *et al.* (1968)
	5365/4090	2″−2	−0.27(8)	AP0	Flynn *et al.* (1976)
			−0.26(6)		
	5522/2165	4′−4	Ad 0.07(12)	AP0	Kutschera *et al* (1968)
			$\lvert\delta\rvert \leq 0.36$	AP0	Broude *et al.* (1976)
	5641/4367	3−2	0.19(4)	AP0	Buhl *et al.* (1967)
			0.18(3)	AP0	Kutschera *et al.* (1968)
			0.16(3)	AP0	Broude *et al.* (1976)
			0.17(2)		
	5641/2283	3−4	$-1.21 \leq \delta \leq -0.26$	AP0	Buhl *et al.* (1967)
			−0.12(17)	AP0	Kutschera *et al.* (1968)
			0.00(10)	AP0	Broude *et al.* (1976)
			−0.05(8)		
	5910/4634	2‴−2	−0.47(4)	AP0	Kutschera *et al.* (1968)
$^{24}_{10}Ne_{14}$	3867/1886	2′−2	0.15(15) or 2.1(6)	AP0	Becker *et al.* (1968)
	5576/3595	2″−2	0.07(7)	AP0	Howard *et al.* (1970)

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
$^{22}_{12}Mg_{10}$	4402/3155	2′−2	0.8(7)	AP0	Rolfs *et al.* (1970)
	5037/3790	2″−2	0.08(15) or 2.1(8)		
	5714/4467	2‴−2	−0.17(10) or 4(2)		
$^{24}_{12}Mg_{12}$	4239/2869	2′−2	Ad−23(9)	AP0	Batchelor *et al.* (1960)
			$\lvert\delta\rvert \geq 30$	AD1	Leccia *et al.* (1973)
			$\delta \geq 20$	AD1	King *et al.* (1977)
	5236/3867	3−2	$\delta \approx \infty$	AP0	Broude and Gove (1963)
			$\delta \leq -19$	AD1	Leccia *et al.* (1973)
			$\delta \geq 7$	AD0	Glavish *et al.* (1973)
	5236/997	3−2′	$5.1^{+1.2}_{-0.8}$ or 0.47(4)	AD1	Leccia *et al.* (1973)
$^{26}_{12}Mg_{14}$	2938/1129	2′−2	−0.12(2)	AP0	Broude and Gove (1963)
			−0.09(5)	AP0	Canada *et al.* (1969)
			−0.16(4)	AP1	Wagner *et al.* (1975)
			−0.11(6)	AD1	King *et al.* (1977)
			−0.12(2)		
	3941/2132	3−2	−0.01(5)	AG1	Ferguson *et al.* (1968)
			0.00(7)	AP1	Nagel *et al.* (1974)
			0.02(3)	AP1	Wagner *et al.* (1975)
			0.01(2)		
	3941/1003	3′−2	−0.06(6)	AG1	Ferguson *et al.* (1968)
			−0.04(5)	AP1	Nagel *et al.* (1974)
			−0.05(10)	AP1	Wagner *et al.* (1975)
			−0.05(4)		
	4350/2541	3′−2	−0.11(6)	AG1	Ferguson *et al.* (1968)
			−0.09(6)	AP1	Nagel *et al.* (1975)
			−0.10(4)		
	4350/1412	3′−2′	Ad$-(0.31^{+0.07}_{-0.05})$	AP1	Nagel *et al.* (1975)
			$-(0.31^{+0.18}_{-0.13})$	AP1	Wagner *et al.* (1975)
	5474/1533	4′−3	Ad−0.27(4)	AP1	Nagel *et al.* (1975)
			−0.27(15)	AP1	Wagner *et al.* (1975)
	5474/1154	4′−4	0.05(19)	AP1	Nagel *et al.* (1975)
			Ad 0.09(7)	AP1	Wagner *et al.* (1975)
$^{28}_{12}Mg_{16}$	4557/3084	2′−2	$\delta \approx 0$	AP0	Chase (1967)
			$\delta = 0.0 \pm 0.1$	AP0	Fintz *et al.* (1972)
			Ad−0.035(30)	AP0	Fisher *et al.* (1973)
	4878/3408	2′−2	−0.36(10)	AP0	Becker (1968)
			$-(0.4^{+0.2}_{-0.1})$	AP0	Fintz *et al.* (1972)
			−0.35(6)	AP0	Fisher *et al.* (1973)
			−0.36(5)		

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
$^{26}_{14}Si_{12}$	2780/990	2′−2	−0.21(10)	AP0	
	3820/2030	3−2	4.7(2.0)		
$^{28}_{14}Si_{14}$	6277/4498	3−2	0.12(5)	AP0	Broude and Gove (1963)
			0.35(9)	AD1	Anyas-Weiss *et al.* (1972)
			0.18(11)	AG1	Carlson *et al.* (1973)
			0.14(2)	AD1	Dalmas *et al.* (1974)
			0.14(2)	$r=1.3$	
	7798/6018	3′−2	−0.10(7)	AG1	Carlson *et al.* (1973)
			or $14^{+\infty}_{-13}$		
	7798/1522	3′−3	$-(0.3^{+0.2}_{-0.4})$		
			or $2.5^{+26.0}_{-1.1}$		
			Ad 3.1(9)	AD1	Dalmas and Petit (1978)
	8589/6810	3″−2	−0.38(3)	AD1	Dalmas *et al.* (1974)
			or −1.5(1)		
$^{30}_{14}Si_{16}$	3498/1263	2′−2	0.18(5)	AP0	Broude and Gove (1963)
			−0.13(25)	AP1	Ohnuma *et al.* (1970)
			0.18(6)	AP0	Symes *et al.* (1971)
			0.17(4)		
	4809/2574	2″−2	−0.52(11)	AP0	Symes *et al.* (1971)
	4809/1311	2″−2′	−0.17(6)		
	4830/2594	3−2	0.65(11)		
	5230/2995	3′−2	0.09(12)		
			or $\lvert\delta\rvert \leq -4$		
	5230/1732	3′−2′	0.12(6)		
	5612/3377	2‴−2	−0.29(4)		
	5612/2114	2‴−2′	0.11(5)		
$^{32}_{14}Si_{28}$	4234/2291	2′−2	−0.84(44)	AP0	Pronko *et al.* (1972)
	5956/4013	2″−2	Ad−0.01(6)	AP0	Pronko *et al.* (1972)
			0.1(2)	AP1	Guillaume *et al.* (1974)
	6385/4442	2‴−2	0.04(4)	AP0	Pronko *et al.* (1972)
			0.5(2)	AP1	Guillaume *et al.* (1974)
$^{32}_{16}S_{16}$	4282/2052	2′−2	$1.4^{+1.4}_{-0.4}$	AP0	Poletti and Groce (1966)
			$29^{+\infty}_{-17}$	AD1	Ingebretson *et al.* (1971)
	5413/3183	3−2	Ad$-(12^{+36}_{-5})$	AP0	Poletti and Grace (1966)
			$\lvert\delta\rvert \geq 20$	AD1	Vernotte *et al.* (1976)
	5549/3319	2″−2	0.55(20)	AP0	Poletti and Grace (1966)
			or $\lvert\delta\rvert > 6$		
$^{34}_{16}S_{18}$	3300/1170	2′−2	−0.133(24)	RG0	Handler and Richardson (1956)
			−0.12(5)	RG0	Fisher *et al.* (1957)
			−0.09(6)	AP0	Moss *et al.* (1970)
			−0.14(6)	AP0	Mulhern *et al.* (1971)
			−0.17(2)	AP1, AG0	Grawe *et al.* (1974)
			−0.148(14)		
	4116/1989	2″−2	−0.57(12)	AP0	Mulhern *et al.* (1971)
			−0.37(5)	AP1, AG0	Grawe *et al* (1974)
			−0.40(5)		

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
$^{36}_{16}S_{20}$	4570/1280	2′−2	0.06(6)	AP0	Olness *et al.* (1971)
			0.08(4)	AP1	Samworth and Olness (1972)
			0.07(4)		
$^{34}_{18}Ar_{16}$	3288/1197	2′−2	0.12(5)	AP1	Grawe *et al.* (1974)
$^{36}_{18}Ar_{18}$	4441/2471	2′−2	$\lvert\delta\rvert \geq 1.5$	AD1	Nolan *et al.* (1976)
	7140/5170	3−2	−1.5(9)	AD1	Hokken *et al.* (1973)
			or −0.32(9)		
	7140/2799	3−2′	−1.49(2)		
			or $-(0.14^{+0.09}_{-0.19})$		
$^{40}_{18}Ar_{22}$	2524/1063	2′−2	$-1 \leq \delta \leq 0$	AG0	Place *et al.* (1971)
			Ad $-(0.41^{+0.13}_{-0.06})$	AP0	Southon *et al.* (1976)
	3207/1476	2″−2	0.11(7)	AP0	Southon *et al.* (1976)
$^{42}_{18}Ar_{24}$	3555/2348	2″−2	$\lvert\delta\rvert \leq 0.07$	AP0	Pronko and McDonald (1973)
$^{40}_{20}Ca_{20}$	5249/1345	2′−2	13^{+6}_{-3}	AD1, AG1	Anderson *et al.* (1969)
$^{42}_{20}Ca_{22}$	2423/899	2′−2	− 0.2(1)	AG0	Martin *et al.* (1966)
			Ad −0.18(2)	AD1	Scott *et al.* (1969)
			−0.09(8)	AP0	Lawley *et al.* (1970b)
	3388/1864	2″−2	$1.7^{+0.5}_{-0.3}$	AP0	Lawley *et al.* (1970b)
	3650/2126	2‴−2	$-(0.08^{+0.03}_{-0.10})$	AD1	Scott *et al.* (1969)
			$\lvert\delta\rvert \leq 0.1$	AP0	Lawley *et al.* (1970b)
			0.06(17)	AP0	Hartmann and Grawe (1971)
			−0.06(5)		
$^{44}_{20}Ca_{24}$	2656/1499	2′−2	−0.14(7)	AG0	Martin *et al.* (1966)
			−0.137(17)	RG0	Walter *et al.* (1968)
			$-(0.15^{+0.09}_{-0.04})$	AP0	Lawley *et al.* (1970a)
			−0.07(3)	RG0	Okano *et al.* (1971)
			−0.123(16)		
	3044/761	4′−4	$-(0.25^{+0.31}_{-0.09})$	AG0	Lawley *et al.* (1970a)
	3776/2619	2″−2	$-(0.62^{+0.08}_{-0.07})$		
$^{48}_{20}Ca_{28}$	4613/781	3−2	0.04(3)	AP0	Tape *et al.* (1971)
$^{44}_{22}Ti_{22}$	2531/1448	2′−2	$-(7.5^{+8.0}_{-2.5})$	AD1	Simpson *et al.* (1971)
$^{46}_{22}Ti_{24}$	2962/2073	2′−2	1.07(15)	AG0	Church *et al.* (1967)
			$1.60^{+0.19}_{-0.17}$	AP0	Lewis *et al.* (1968)
			$1.15^{+0.50}_{-0.40}$	AP0	Horoshko *et al.* (1968)
			1.28(18)	$r=1.6$	
			3.1(9)	AD1	Gallmann *et al.* (1971)
	3236/2346	2″−2	−0.06(16)	AP0	Lewis *et al.* (1968)
			0.0(1)	AP0	Horoshko *et al.* (1968)
			0.10(14)	AD1	
			0.01(7)		

TABLE I.[l] *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
$^{48}_{22}Ti^{\dagger}_{26}$	2421/1438	2′−2	0.18(9)	AG0	Martin *et al.* (1966)
			$0.11^{+0.13}_{-0.11}$	AP0	Monahan *et al.* (1969)
			0.15(7)		
	3631/2648	2‴−2	−0.18(4)	AP0	Monahan *et al.* (1969)
$^{50}_{22}Ti_{28}$	4311/2755	2′−2	0.26(17)	AP0	Pronko, Bardin, Becker, Fisher, McDonald, and Poletti (1974, erratum)
$^{52}_{22}Ti_{30}$	2259/121	2′−2	0.03(10)	AP0	Pronko, Bardin, Becker, Fisher, McDonald, and Poletti (1974)
	2428/1381	2″−2	−0.39(8)		
$^{50}_{24}Cr_{26}$	2922/2136	2′−2	0.03	AG0	Twin and Willmott (1966)
			$0.03^{+0.06}_{-0.04}$	AP0	Mo *et al.* (1968)
	3156/2370	2″−2	−0.14	AG0	Twin and Willmott (1966)
			$-(0.24^{+0.09}_{-0.07})$	AP0	Mo *et al.* (1968)
	3692/2906	2‴−2	−0.84	AG0	Twin and Willmott (1966)
			$-(0.71^{+0.23}_{-0.20})$	AP0	Mo *et al.* (1968)
$^{52}_{24}Cr_{28}$	2966/1532	2′−2	$-(0.12^{+0.17}_{-0.13})$	RG0	Malmskog (1963)
			Ad −6.25(1.50)	AG0	Kaye *et al.* (1965)
			$-5.6^{+\infty}_{-2.8}$	AP0	Monahan *et al.* (1968)
	3162/1728	2″−2	Ad −0.175(65)	AG0	Kaye and Cressy (1965)
			$-(0.6^{+1.9}_{-0.7})$	AP0	Monahan *et al.* (1968)
$^{54}_{24}Cr_{30}$	2620/1785	2′−2	$-1.1 \leq \delta \leq -0.3$*	RG0	White (1963)
			$-(0.22^{+0.15}_{-0.10})$	RG0	Bartholomeu and Gunye (1965)
			$-(0.36^{+0.29}_{-0.14})$		
	3074/2239	2″−2	0.10(8)	RG0	White (1963)
			0.10(6)	RG0	Bartholomew and Gunye (1965)
			0.10(5)		
	3437/2602	2‴−2	0.09(10)	RG0	White (1963)
			−0.04(15)	RG0	Bartholomew and Gunye (1965)
			0.04(8)		
$^{56}_{24}Cr_{32}$	1832/825	2′−2	−1.8(1.0)	AP0	Bardin *et al.* (1976)
	2328/1320	2″−2	0.17(30)		
$^{54}_{26}Fe_{28}$	2959/1550	2′−2	0.25(19)	AP0	Thomas *et al.* (1966)
			$0.0 \leq \delta \leq 2.2$	AD0	Benjamin and Morgan (1967)
			Ad 0.11(4)	AP1	Moss *et al.* (1972)
	3164/1755	2″−2	$-(0.6^{+0.4}_{-0.3})$	AP0	Thomas *et al.* (1966)
			or $\lvert\delta\rvert \geq 3$		
			$0.6^{+0.6}_{-0.3}$	AP1	Moss *et al.* (1972)
			or $\lvert\delta\rvert \geq 2.4$		
	3345/806	3−4	$\lvert\delta\rvert \leq 0.14$ or $\delta \geq 3.5$	AP1	Moss *et al.* (1972)
	3345/1936	3−2	$-(0.7^{+2.3}_{-0.2})$		

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
$^{56}_{26}Fe_{30}$	2658/1811	2′−2	−0.15(8)	RG0	Metzger and Todd (1953)
			−0.16(4)	RG0	Levine *et al.* (1958)
			−0.19(2)	RD0	Dagley *et al.* (1959)
			−0.11(6)	RD0	Bauer and Deutsch (1960)
			−0.15(4)	AD0	Trehan *et al.* (1967)
			−0.20(2)	AG0	Kreische *et al.* (1969)
			−0.19(3)	RG1	Hofmann (1974)
			−0.14(3)	AD1	Sarantites *et al.* (1976)
			−0.179(11)		
			−0.06(2)	RG0	Stimac *et al.* (1959)
	2960/2113	2″−2	0.29(6)	RG0	Metzger and Todd (1953)
			0.27(2)	RG0	Levine *et al.* (1958)
			0.28(2)	RG0	Stimac *et al.* (1959)
			0.35(4)	RD0	Dagley *et al.* (1959)
			0.20(4)	AD0	Trehan *et al.* (1959)
			0.27(3)	RG1	Hofmann (1974)
			0.275(11)		
	3123/1038	4′−4	−0.01(4)	RG1	Agarwal *et al.* (1971)
			−0.02(2)	RG1	Taylor and Singh (1971)
			−0.02(2)	RG1	Hofmann (1974)
			−0.01(4)	AD1	Sarantites *et al.* (1976)
			−0.16(11)	AD1	Bendjaballah *et al.* (1977)
			−0.02(1)		
	3370/2523	2‴−2	0.25(15)	RG1	Hofmann (1974)
$^{58}_{26}Fe_{32}$	1674/864	2′−2	−0.57(6)	AG0	Schmidt *et al.* (1969)
			−0.57(6)		
			−0.53(4)		
			−0.45(6)		
			$0.49 < \delta < 0.83$		
			$-(0.61^{+0.19}_{-0.10})$	RG1	Singhal *et al.* (1971)
			−0.69(5)	RD1	Fox *et al.* (1972)
			−0.56(3)	$R=1.5$	
			−2.2(3)	RG0	Frauenfelder *et al.* (1956)
			$-(1.5^{+0.5}_{-0.4})$	RG0	MacArthur *et al.* (1962)
			−1.6(2)	RG0	Malmskog (1964)
			−1.57(4)	RG0	Rama Mohan *et al.* (1966)
			−1.46(7)	RG0	Singh *et al.* (1969)
			−1.1(2)	RG0	Schotzig *et al.* (1969)
			$-(0.94^{+0.08}_{-0.09})$	RG0	Fox *et al.* (1972)
			$-(1.0^{+0.6}_{-0.2})$	RG1	Fox *et al.* (1972)
	2133/1322	3−2	$-(0.48^{+0.12}_{-0.10})$	AG0	Schmidt *et al.* (1969)
	2876/2066	2″−2	$-(0.33^{+0.18}_{-0.11})$		
	3084/2273	2‴−2	−0.05(2)		
			$-(0.02^{+0.04}_{-0.03})$		
			−0.04(2)		
$^{60}_{26}Fe_{34}$	2305/1481	2′−2	$4.3^{+3.8}_{-1.5}$	AD1	Warburton *et al.* (1977)
			or $-(0.27^{+0.13}_{-0.11})$		

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
$^{58}_{28}Ni_{30}$	2775/1321	2′−2	$-(1.5^{+1.5}_{-0.4})$	AP0	Horoshko *et al.* (1967)
			$-(1.14^{+0.19}_{-0.11})$	AD1	Van Patter *et al.* (1969)
			$-(1.2^{+0.8}_{-0.2})$	AD1	Scott *et al.* (1969)
			$-(1.3^{+0.6}_{-0.3})$	AP0	Alberts *et al.* (1970)
			−1.1(2)	AP0, AP1	Start *et al.* (1971)
			−1.14(11)		
	3038/1584	2″−2	0.10(15)	AP0	Horoshko *et al.* (1967)
			0.19(6)	AD1	Van Patter *et al.* (1969)
			0.19(6)	AD1	Scott *et al.* (1969)
			$0.19^{+0.13}_{-0.09}$	AP0	Alberts *et al.* (1970)
			0.12(12)	AP0, AP1	Start *et al.* (1971)
			0.18(4)		
	3038/263	2″−2′	−0.03(25) or $2.4^{+3.5}_{-0.9}$	AD1	Van Patter *et al.* (1969)
	3263/1809	2‴−2	0.4(2)	AP0	Horoshko *et al.* (1967)
			$0.64^{+0.28}_{-0.22}$	AD1	Scott *et al.* (1969)
			$1.2 \geq \delta \geq 0.36$	AP0	Alberts *et al.* (1970)
			$0.70^{+0.30}_{-0.35}$	AP0, AP1	Start *et al.* (1971)
			0.56(13)		
	3420/961	3−4	−0.02(3)	AD1	Van Patter *et al.* (1969)
			0.03(3)	AP0	Alberts *et al.* (1970)
			0.0(1)	AP0, AP1	Start *et al.* (1971)
			0.00(2)		
	3420/383	3−2″	0.08(9)	AD1	Van Patter *et al.* (1969)
	3620/1161	4′−4	$0.64^{+0.32}_{-0.56}$	AD1	Van Patter *et al.* (1969)
			−0.14(17)	AP0, AP1	Start *et al.* (1971)
			−0.04(7)	AG1	Ballini *et al.* (1976)
			−0.05(6)		
$^{60}_{28}Ni_{32}$	2159/827	2′−2	$0.2 \leq \delta \leq 1.5$	AD0	Sen Gupta and Van Patter (1963)
			0.7(3)	AD0	Mohindra and Van Patter (1965a,b)
			1.2(3)	RG0	Shafroth and Wood (1966)
			0.68(22)	AD0	Van Patter *et al.* (1972)
			0.82(15)		
			$-(6^{+10}_{-2})$	RG0	Levine *et al.* (1958)
	2626/1294	3−2	−2.1(1)	AD1	Moazed *et al.* (1971)
	2626/467	3−2′	$\lvert\delta\rvert > 30$	AD0	Mohindra and Van Patter (1965a,b)
			Ad $-(40^{+20}_{-10})$	AD1	Moazed *et al.* (1971)
	3124/1792	2″−2	−0.15(9)	RG0	Levine *et al.* (1958)
			−0.24(6)	AD0	Mohindra and Van Patter (1965a,b)
			−0.21(4)	RG0	Shafroth and Wood (1966)
			Ad −0.53(3)	AD1	Moazed *et al.* (1971)
	3124/498	2″−3	0.15(15)	AD1	Moazed *et al.* (1971)
	3186/1854	3′−2	0.11(2)		
	3186/1027	3′−2′	0.42(3)		
	3186/680	3′−4	0.09(2)		

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
$^{62}_{28}Ni_{34}$	2302/1129	2′−2	$\|\delta\| > 1$	AG0	Fanger *et al.* (1970)
			Ad 3.2(1)	AD1	Van Patter *et al.* (1972)
			$3.0^{+2.0}_{-0.7}$	RG1	Casanova *et al.* (1976)
	2891/1718	2″−2	$-(4.1^{+3.0}_{-1.3})$	AG0	Fanger *et al.* (1970)
	3059/1886	2‴−2	$0.65^{+0.15}_{-0.20}$		
$^{62}_{30}Zn_{32}$	1805/851	2′−2	$-(1.2^{+0.5}_{-0.4})$	AD1	Bruandet *et al.* (1976)
	2384/1805	3−2	−0.5(1)		
$^{64}_{30}Zn_{34}$	1799/807	2′−2	$-3 \geq \delta \geq -6$	AD0	Sen Gupta and Wood (1963)
			−0.45(5)	AD1	Aleksandrov *et al.* (1977)
			−1.3(3)	AD1	Wells *et al.* (1978)
			−3.3(7)	AD1	Simister *et al.* (1978)
			$-1.6(4)^{\dagger}$		
	2736/430	4′−4	−0.2(3) or 1.7(5)	AD1	Wells *et al.* (1977)
	2794/1802	2″−2	0.7(5)	AD1	Simister *et al.* (1978)
	2979/1987	3−2	0.26(3)		
	2979/1180	3−2′	−0.05(3)		
	3005/2013	2‴−2	−0.06(10)		
	3005/1206	2‴−2′	0.6(5)		
$^{66}_{30}Zn_{36}$	1872/833	2′−2	−2.2(4)	RG0	Schwarzchild and Grodzins (1960)
			$-0.8 \geq \delta \geq -3.5$	AD0	Sen Gupta and Wood (1963)
			−1.9(3)	RG0	Hayashi *et al.* (1969)
			−2.0(2)		
$^{68}_{30}Zn_{38}$	1883/806	2′−2	−1.45(15)	AG0	Ottmar *et al.* (1971)
			−1.46(14)	RG1	Lange *et al.* (1973)
			−1.46(10)		
			4^{+3}_{-2}	RG0	Kono (1962)
	2339/1261	2″−2	$-(0.23^{+0.06}_{-0.04})$	AG0	Ottmar *et al.* (1971)
			−0.14(4)	RG1	Lange *et al.* (1973)
			−0.18(5)	$r = 1.7$	
			−1.8(2)	RG0	Ramaswamy and Jastraw (1960)
			−2.25(30)	RG0	Taylor and McPherson (1963)
	2822/1745	2‴−2	0.24(13)	AG0	Ottmar *et al.* (1971)
			0.29(5)	RG1	Lange *et al.* (1973)
			0.28(5)		
$^{66}_{32}Ge_{34}$	1693/736	2′−2	Ad $-(3.3^{+2.6}_{-1.8})$	AD1	Wadsworth *et al.* (1979)
			$-(25^{+65}_{-11})$	AD1	Soundranayagam *et al.* (1981)
$^{68}_{32}Ge_{36}$	1778/762	2′−2	$-(0.2^{+0.1}_{-0.2})$	AD1	Morand *et al.* (1977)
			Ad −0.09(2)	AD1	de Lima *et al.* (1979)
	2429/651	3−2′	$-(0.2^{+0.5}_{-0.1})$	AD1	Morand *et al.* (1977)
			Ad −0.02(2)	AD1	de Lima *et al.* (1979)

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
$^{70}_{32}Ge_{38}$	1709/668	2′−2	Ad−$(5.0^{+4.0}_{-1.5})$	AD0	Mohindra and Van Patter (1965)
			−(6^{+10}_{-3})	AD1	Chung *et al.* (1970)
$^{72}_{32}Ge_{40}$	1464/630	2′−2	10^{+15}_{-4}	RG0	Arns and Wiedenbeck (1958)
			$\lvert\delta\rvert \geq 4$	RG0	Coleman (1958)
			5^{+10}_{-2}	AD0	Mohindra and Van Patter (1965)
			$\lvert\delta\rvert \geq 10^{*}$	RG1	Monahan *et al.* (1969)
			5^{+3}_{-1}	AD1	Chung *et al.* (1970)
			Ad−10.3(1.3)	RG2	Chen *et al.* (1974)
	2065/1231	3−2	$-0.44 \geq \delta \geq -4.3$	RG1	Monahan *et al.* (1969)
	2065/601	3−2′	$\lvert\delta\rvert \geq 3$	RG1	Monahan *et al.* (1969)
			Ad−$(42^{+\infty}_{-18})$	RG2	Chen *et al.* (1974)
$^{74}_{32}Ge_{42}$	1204/608	2′−2	$0.5 \leq \delta \leq 12$	RG0	Yamazaki *et al.* (1960)
			$3.4^{+1.6}_{-1.1}$	RG0	Eichler *et al.* (1962)
			$3.7^{+1.5}_{-1.1}$	RG1	
			2.9(8)	RG0	Schotzig *et al.* (1969)
			3.0(1.0)	AD1	Chung *et al.* (1970)
			3.4(4)	RG1	Cambiaggio *et al.* (1975)
			3.3(3)		
	2198/994	2″−2′	Ad−2.8(2)	RG1	Cambiaggio *et al.* (1975)
			$-1.4 \geq \delta \geq -3.8$		
$^{76}_{32}Ge_{44}$	1109/545	2′−2	Ad 3.5(1.5) or 0.1(3)	AD1	Chung *et al.* (1970)
$^{72}_{34}Se_{38}$	1317/455	2′−2	4.6(1.5)	AD1	Crowell (1975)
	2294/1431	2″−2	$2.2^{+\infty}_{-0.2}$		
	2294/977	2″−2′	6.7(3)		
	2372/1055	3−2′	$3.4^{+\infty}_{-1.5}$		
$^{74}_{34}Se_{40}$	1270/635	2′−2	−$(5.6^{+2.1}_{-1.1})$	RG2	Coban *et al.* (1972)
			−2.6(2)	RG1	Cambiaggio *et al.* (1975)
			−$(3.6^{+2.0}_{-1.0})^{\dagger}$		
	1884/615	3−2′	0.3(1)	AD1	Piercey *et al.* (1979)
$^{76}_{34}Se_{42}$	1216/657	2′−2	$7.3^{+1.6}_{-1.1}$	RG0	Lindgvist and Marklund (1957)
			$4.8^{+5.0*}_{-2.0}$	RG0	Coleman (1958)
			5.5(4)	RG0	Grabowski and van Nooije *et al.* (1960)
			$5.0^{+39.0}_{-2.4}$	AD1	Lieder and Draper (1970)
			$6.1^{+0.9}_{-0.7}$	RG2	Nagahara (1973)
			5.2(2)	RD1	Barclay *et al.* (1976)
			5.4(2)†		
			−(22^{+16}_{-7})	RG0	Funk and Wiedenbeck (1958a)
	1788/1229	2″−2†	0.06(2)	RG0	Grabowski *et al.* (1960)
			$-0.1 \leq \delta \leq 1.0^{*}$	RG0	Sathoff *et al.* (1963)
			−$(0.94^{+0.10}_{-0.12})$	RG2	Nagahara (1973)
			−0.49(5) or $\delta \leq -16$	RD1	Barclay *et al.* (1976)

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)		Method	Reference
$^{78}_{34}Se_{44}$	1309/695	2′−2	$6.2^{+8.0}_{-2.3}$ or −0.26(10)	AD1	Lieder and Draper (1970)	
			$2.5^{+0.7}_{-0.6}$* or −0.03(9)	AD1	Barrette *et al.* (1974)	
			Ad $3.5^{+2.6}_{-1.2}$ or −0.14(12)	$r=1.8$		
$^{80}_{34}Se_{46}$	1450/783	2′−2	Ad $-(5^{+6}_{-2})$ or $-(0.71^{+0.17}_{-0.12})$	AD1	Barrette *et al.* (1974)	
$^{80}_{36}Kr_{44}$	1256/639	2′−2	$16^{+\infty}_{-8}$	RG0	Ramayya *et al.* (1967)	
$^{82}_{36}Kr_{46}$	1475/698	2′−2	$5.8^{+22.0}_{-5.3}$	RG0	Sakai *et al.* (1962)	
			$1.1 \leq \delta \leq 4.8$	RG0	Simons *et al.* (1964)	
			$1.1 \leq \delta \leq 3.7$	RG0	Etherton and Kelly (1966)	
			1.65(15)	RG0	Koch *et al.* (1967)	
			$0.8 \leq \delta \leq 6.4$	RG0	Gupta and Rajaj (1968)	
			$1.0^{+3.0}_{-1.0}$	AD1	McCauley and Draper (1971)	
			3.0(3)	RG0	Satyanarayana and Lakshminarayana (1972)	
			2.55(32)	RG2	Gardulski and Wiedenbeck (1973)	
			$1.7 \leq \delta \leq 2.8$†			
			−2.7(3)	RD1	Callaghan *et al.* (1977)	
	2094/1318	3−2	4.0(2)	RG0	Waddell and Jensen (1956)	
			4.2(2)	RG0	Benczer-Koller (1958)	
			4.4(2)	RG0	Etherton and Kelly (1966)	
			4.4(4)*	RG0	Gupta and Bajaj (1968)	
			4.2(2)	RG0	Satyanarayana and Lakshminarayana (1972)	
			3.1(6)	RD1	Callaghan *et al.* (1977)	
			4.2(1)†			
	2094/619	3−2′	2.3(6)*	RG0	Waddell and Jensen (1956)	
			2.1(1)*	RG0	Benczer-Koller (1958)	
			2.6(4)	RG0	Simons *et al.* (1964)	
			2.0(3)	RG0	Etherton and Kelly (1966)	
			2.1(2)*	RG0	Satyanarayana and Lakshminarayana (1972)	
			1.93(7)	RG2	Gardulski and Wiedenbeck (1973)	
			2.2(4)	RD1	Callaghan *et al.* (1977)	
			2.13(7)†	$r=1.8$		
			10^{+90}_{-8}	AD1	McCauley and Draper (1971)	
$^{84}_{36}Kr_{48}$	1893/1012	2′−2	$-(36^{+\infty}_{-25})$	RG0	Roalsvig and Casper (1965)	
$^{86}_{38}Sr_{48}$	1854/777	2′−2	0.32(3)	RG0	Yamazaki *et al.* (1962)	
			0.28(3)	RG1	Arns *et al.* (1970)	
			0.30(2)			
$^{88}_{38}Sr_{50}$	3219/1382	2′−2	$-(0.06^{+0.09}_{-0.07})$	RG0	Shastry and Bhattacharyya (1964)	
		2′−2	Ad 0.04(2)	RG0	Kawase (1970)	
$^{88}_{40}Zr_{48}$	1819/761		−0.10(13)	AD1	Numao *et al.* (1979)	
$^{92}_{40}Zr_{52}$	1847/913	2′−2	0.020(70)	RG0	Coleman (1958)	

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy(keV)		δ(E2/M1)	Method	Reference
			0.010(24)	RG0	West *et al.* (1959)
			0.044(17)	RG0	Bunker *et al.* (1962)
			−0.007(33)	RG1	Collins *et al.* (1978)
			−0.13(5)	AD1	Glasgow *et al.* (1978)
			0.016(12)		
	2066/1132	2″−2	−1.04(11)	AD1	Glasgow *et al.* (1978)
$^{94}_{40}Zr_{54}$	1671/752	2′−2	−0.22(10)	AD1	Glasgow *et al.* (1978)
	2150/1232	2″−2	$-(1.7^{+0.8}_{-1.4})$		
$^{94}_{42}Mo_{52}$	1864/993	2′−2	−2.0(3)	RG0	Aras *et al.* (1968)
	2393/1522	2″−2	$-(1.9^{+0.5}_{-0.4})$		
$^{96}_{42}Mo_{54}$	1498/720	2′−2	0.44(3)	RG0	Heck *et al.* (1970)
			0.36(11)	RG2	Barrette *et al.* (1971)
			0.43(3)		
	1626/848	2″−2	$-(1.05^{+0.10}_{-0.09})$	RG0	Heck *et al.* (1970)
	1978/1200	3−2	1.41(19)*	RG0	Simons *et al.* (1962)
			1.30(30)		
			1.29(13)	RG0	Monaro *et al.* (1968)
			$1.2^{+1.3}_{-0.5}$		
			1.65(30)	RG0	Heck *et al.* (1970)
			1.41(28)	RG2	Barrette *et al.* (1971)
			1.36(9)		
$^{98}_{42}Mo_{56}$	1432/645	2′−2	0.58(5)	RG0	Heck *et al.* (1970)
	1759/971	2″−2	−2.15(15)		
$^{96}_{44}Ru_{52}$	1931/1099	2′−2	$-(4.2^{+2.2}_{-1.4})$	AP1	Lange *et al.* (1979)
	2284/1451	2″−2	0.03(10)		
	2526/1693	2‴−2	−0.34(9)		
			or $\delta \geq 6$		
$^{98}_{44}Ru_{54}$	1414/762	2′−2	$13.4^{+3.9}_{-2.5}$	AD1	Lange *et al.* (1979)
$^{100}_{44}Ru_{56}$	1366/822	2′−2	$0.6 \leq \delta \leq 6.4$*	RG0	Koike *et al.* (1964)
			$3.5^{+3.6}_{-1.7}$		
			$5.4^{+1.6}_{-1.1}$	RG0	Kawakami and Hisatake (1968)
			$3.2^{+0.3}_{-0.4}$		
			$6.2^{+3.3}_{-1.5}$		
			$8^{+\infty}_{-5}$	RG0	Berzins *et al.* (1969)
			$3.4^{+0.8}_{-0.6}$	RG1	Babenko *et al.* (1978)
			3.5(4)		
			$3.9^{+0.9}_{-0.6}$		
			3.8(4)		
	1880/1340	3−2	$0.22^{+0.07}_{-0.05}$	RG0	Koike *et al.* (1964)
			$0.53^{+1.20}_{-0.15}$	RG0	
			$0.45^{+1.5}_{-0.2}$	RG1	Babekno *et al.* (1978)
			$0.41^{+0.22}_{-0.12}$		
			0.54(11)		
			$0.36^{+0.14}_{-0.11}$	$r=2.1$	

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
$^{102}_{44}Ru_{58}$	1103/628	$2'-2^{\dagger}$	$-5.5(5)$	RG0	Hisatake (1961)
			5^{+12}_{-3}	RG2	Konijn *et al.* (1968)
			$-(97^{+\infty}_{-67})$	RG1	Singh and Taylor (1970b)
	1522/1046	$3-2$	$-(6.7^{+0.9}_{-0.7})$	RG1	Singh and Taylor (1970b)
	1522/419	$3'-2$	$-(7.9^{+2.1}_{-1.4})$		
	1581/1106	$2''-2$	0.28(3)		
	2037/1562	$2'''-2$	$-2.7(2)$	RG0	McGowan and Stelson (1961a)
			$-(2.1^{+0.6}_{-0.5})$	RG0	Born *et al.* (1963)
			$-(2.2^{+0.4}_{-0.3})$	RG1	Singh and Taylor (1970b)
			$-2.6(2)$		
$^{104}_{44}Ru_{60}$	893/535	$2'-2$	$-(8.5^{+2.5}_{-1.5})$	AD1	McGowan *et al.* (1968)
			$-(36^{+54}_{-14})$	RG2	Summerer *et al.* (1978)
			$-(18^{+6}_{-4})$		
$^{102}_{46}Pd_{56}$	1534/978	$2'-2$	$10.4^{+12.1}_{-3.7}$	AP1	Lange *et al.* (1977)
	1944/1388	$2''-2$	$8.1^{+7.3}_{-2.6}$		
	2112/1556	$3-2$	$\lvert\delta\rvert \geq 15$	AD1	Grau *et al.* (1976)
			$\lvert\delta\rvert \geq 15$	AP1	Lange *et al.* (1977)
$^{104}_{46}Pd_{58}$	1342/786	$2'-2$	$\lvert\delta\rvert \geq 5$*	RG1	Okano *et al.* (1972)
			$\lvert\delta\rvert \geq 8$	RG1	Singhal *et al.* (1972)
			Ad 11^{+10}_{-3}	RG1	Babenko *et al.* (1978)
			$-4.8(4.2)$	AD1	Grau *et al.* (1976)
	1821/1265	$3-2$	$\lvert\delta\rvert \geq 13$ or 0.23(7)	AD1	Grau *et al.* (1976)
			Ad$-(2.8^{+3.1}_{-0.3})$	RG1	Babenko *et al.* (1978)
	2082/759	$4'-4$	$-(0.4^{+0.14}_{-0.10})$	RG1	Okano *et al.* (1972)
			$-0.84(24)$	AD1	Grau *et al.* (1976)
$^{106}_{46}Pd_{60}$	1128/616	$2'-2$	$-(30^{+\infty}_{-15})$	RG0	Robinson *et al.* (1960)
			$-(8.3^{+4.6}_{-2.3})$*	RG0	Hattula and Liukkonen (1968)
			$\lvert\delta\rvert \geq 6$*	RG2	Weight *et al.* (1968)
			$-(12^{+15}_{-5})$	AD1	Robinson *et al.* (1969b)
			$\lvert\delta\rvert \geq 10$	RG2	Hsue *et al.* (1975)
			$-(10^{+4}_{-2})$	RD1	Schoeters *et al.* (1975)
			$-(10^{+\infty}_{-6})$	AD1	Grau *et al.* (1976)
			$-(8.3^{+0.6}_{-0.5})$	RG1	Tivin *et al.* (1977)
			$-38^{+\infty}_{-18}$	RD1	Ruhter (1977)
			$-8.9(5)$		
			$-(4.3^{+1.3}_{-0.8})$	RG0	Koch *et al.* (1967)
			$-(27^{+16}_{-8})$	RG1	Avignone and Pinkerton (1973)
	1558/1046	$3-2$	$-3.1(2)$	RD1	Schoeters *et al.* (1975)
			$-4.5(1.3)$	AD1	Grau *et al.* (1976)
			$-5.2(6)$	RG1	Tivin *et al.* (1977)
			$-5.0(7)$		
			$-2.4(8)$		
			$-3.6(3)^{\dagger}$	$r=1.7$	

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
	1558/430	3−2′	Ad−7.4(7)	RD1	Schoeters *et al.* (1975)
			$\delta \leq -12$	AD1	Grau *et al.* (1976)
			7^{+30}_{-3}	RG1	Tivin *et al.* (1977)
	1562/1050	2″−2	0.21(1)*	RG0	Klema and McGowan (1958)
			0.19(2)	RG0	Hattula and Liukkonen (1968)
			$0.1 \leq \delta \leq 0.5$	RG0	Weight *et al.* (1968)
			0.30(7)	RG2	Hsue *et al.* (1975)
			0.24(1)	RG1	
			0.23(4)		
			0.16(1)	RD1	Ruter *et al.* (1977)
			0.20(1)	$r=1.7$	
	1932/703	4′−4	−1.1(4)	RD1	Schoeters *et al.* (1975)
			−2.3(2)	RG1	Tivin *et al.* (1977)
			−2.0(2)		
	2189/1061	2‴−2	−1.20(15)	RG1	Avignone and Pinkerton (1973)
$^{108}_{46}Pd_{62}$	931/497	2′−2	$-5.2^{+2.5}_{-1.4}$	AD1	Robinson *et al.* (1969b)
			Ad−3.1(4)	AG1	Robinson *et al.* (1971)
	1441/1007	$2''-2^{\dagger}$	$-(20^{+\infty}_{-13})$	RG1	Singhal *et al.* (1973)
$^{110}_{46}Pd_{64}$	814/440	2′−2	$-(4.6^{+1.9}_{-1.2})$	AP1	Robinson *et al.* (1969b)
$^{106}_{48}Cd_{58}$	1718/1085	2′−2	−0.60(20)	AD1	Milner *et al.* (1969)
			−0.85(20)	AG1	Grabowski and Robinson (1973)
			−0.73(14)		
	2105/611	4′−4	−0.31(6)	AD1	Stromswold *et al.* (1978)
			−0.34(4)	AD1	Samuelson *et al.* (1979)
			−0.33(3)		
$^{108}_{48}Cd_{58}$	1603/970	2′−2	$-(1.5^{+1.5}_{-0.6})$	AD1	Milner *et al.* (1969)
$^{110}_{48}Cd_{62}$	1476/818	2′−2	$-(1.5^{+0.9}_{-0.4})$	AD1	Milner *et al.* (1969)
			−1.20(15)	RG2	Krane and Steffen (1970)
			−1.20(7)	RG2	Gardulski and Wiedenbeck (1973)
			−1.36(10)	RD1	Johnston and Stone (1973)
			−1.42(9)	RG2	Ruhter (1977)
			$-(1.5^{+2.0}_{-0.6})$		
			−1.2(5)	RD1	Wang *et al.* (1978)
			$-(1.25^{+0.22}_{-0.10})$	RG1	Verma *et al.* (1979)
			−1.30(4)		
	1784/1126	2″−2	$0.06^{+0.12}_{-0.07}$	RG1	Kawase *et al.* (1972)
			0.3(2)	AD1	Demidov *et al.* (1976b)
			0.12(10)		
	2162/1505	3−2	$-(0.54^{+0.46}_{-0.19})$	RG0	Funk and Wiedenbeck (1958b)
			$-(0.37^{+0.32}_{-0.21})$*	RG0	Knipper (1958)
			−0.47(5)*	RG0	Munnich *et al.* (1964)
			−0.88(45)	RD0	Westenbarger *et al.* (1965)
			−0.48(3)	RG2	Krane and Steffen (1970)
			$-(0.33^{+0.14}_{-0.10})$		
			$-(0.49^{+0.30}_{-0.17})$*	RG0	Sud *et al.* (1970)

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
			$-(0.46^{+0.18}_{-0.10})$	RG1	Gardulski and Wiedenbeck (1973)
			−0.48(3)	RD1	Johnston and Stone (1973)
			$-(0.2^{+0.2}_{-0.1})$	AD1	Demidov *et al.* (1976b)
			$-(0.4^{+0.17}_{-0.09})$	RG1	Verma *et al.* (1979)
			−0.48(2)†		
			$-(0.84^{+0.51}_{-0.14})$*	RG1	Gardulski and Wiedenbeck (1973)
			−1.2(2)	RG2	Ruhter (1977)
			−1.2(4)		
			−1.09(9)	RD1	Wang *et al.* (1978)
			−1.11(8)†		
	2162/686	3−2′	$-(1.1^{+0.8}_{-0.4})$	RG2	Krane and Steffen (1970)
			−1.80(5)	RD1	Johnston and Stone (1973)
			$-(1.3^{+0.8}_{-0.4})$	RG2	Ruhter (1977)
			−1.65(9)	RD1	Wang *et al.* (1978)
			$-(1.5^{+2.2}_{-0.6})$	RG1	Verma *et al.* (1979)
			Ad† −1.76(4)		
			$0.4^{+0.1}_{-0.2}$	AD1	Demidov *et al.* (1976b)
	2220/678	4′−4	$-(0.4^{+0.8}_{-0.5})$	RG2	Krane and Steffen (1970)
			$-(0.4^{+0.6}_{-0.4})$		
			$-(0.24^{+0.06}_{-0.04})$	RG2	Gardulski and Wiedenbeck (1973)
			$-(0.29^{+0.22}_{-0.08})$		
			−0.44(5)	RD1	Johnson and Stone (1973)
			$-(0.24^{+0.22}_{-0.08})$	RG2	Ruhter (1977)
			−0.33(7)		
			−0.36(3)	RD1	Wang *et al.* (1978)
			−0.25(15)	RG1	Verma *et al.* (1979)
			−0.35(3)	$r=1.4$	
$^{112}_{48}Cd_{64}$	1312/695	2′−2	−0.87(10)	AD1	Milner *et al.* (1969)
			−0.77(6)	AG1	Grabowski and Robinson (1973)
			−0.80(5)†		
	1468/851	2″−2	0.05(11)	AD1	Milner *et al.* (1969)
			0.22(5)	RG0	Wallace *et al.* (1972)
			0.21(6)	RG1	Kawase *et al.* (1972)
			0.10(7)	AG1	Grabowski and Robinson (1973)
			0.16(4)		
			−0.1(1)	AD1	Demidov *et al.* (1976a)
	2064/1447	3−2	−0.3(1)		
	2064/752	3−2′	$0.07^{+0.02}_{-0.03}$		
	2231/1613	2‴−2	0.00(6)	RG0	Wallace *et al.* (1972)
			0.10(10)	AD1	Demidov *et al.* (1976a)
			0.03(5)		
$^{114}_{48}Cd_{66}$	1208/650	2′−2	$-(1.5^{+0.9}_{-0.5})$	AD1	Milner *et al.* (1969)
			$-(1.4^{+0.7}_{-0.3})$	AG1	Grabowski and Robinson (1973)
			$-(1.0^{+0.5}_{-0.2})$	AD1	Demidov *et al.* (1976b)
			$-(1.22^{+0.37}_{-0.16})$		

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
	1363/804	2″−2	0.15(15)	AD1	Milner *et al.* (1969)
			$0.05^{+0.11}_{-0.17}$	AG1	Grabowski and Robinson (1973)
			$0.09^{+0.08}_{-0.12}$		
	1863/1305	3−2	$-(0.10^{+0.06}_{-0.02})$	AD1	Demidov *et al.* (1976b)
$^{116}_{48}Cd_{68}$	1212/699	2′−2	$-(1.5^{+0.9}_{-0.5})$	AD1	Milner *et al.* (1969)
			$-(1.5^{+0.5}_{-0.3})$	AD1	Demidov *et al.* (1976b)
			$-(1.5^{+0.4}_{-0.2})$		
$^{112}_{50}Sn_{62}$	2154/895	2′−2	$+3.8^{+2.5}_{-1.0}$	AD1	Demidov *et al.* (1978)
$^{116}_{50}Sn_{66}$	2112/819	2′−2	−1.81(13)	RG1	Garcia-Bermudez *et al.* (1974)
			−1.52(27)	RG1	Yamaguchi *et al.* (1975)
			$-(1.5^{+0.4}_{-0.3})$	AD1	Demidov *et al.* (1978)
			−1.5(4)	AD1	Bron *et al.* (1979)
			$-1.71(12)^{\dagger}$		
	2225/932	2″−2	$-(1.9^{+0.7}_{-0.5})$	RG1	Kantele *et al.* (1979)
$^{118}_{50}Sn_{68}$	2043/813	2′−2	$-(5^{+5}_{-2})$	AD1	Demidov *et al.* (1978)
			$-(12^{+\infty}_{-7})$	AD1	Bron *et al.* (1979)
			$-(7^{+6}_{-3})$		
$^{120}_{50}Sn_{70}$	2096/925	2′−2	Ad−1.43(25)	AD1	Kikuchi and Sugiyama (1974)
			$-(10^{+\infty}_{-5})$	AD1	Demidov *et al.* (1978)
	2355/1184	2″−2	3.4(1.8)		
$^{122}_{50}Sn_{72}$	2153/1013	2′−2	4^{+2}_{-1}	AD1	Demidov *et al.* (1978)
$^{124}_{50}Sn_{74}$	2130/998	2′−2	$3.0^{+1.2}_{-0.6}$	AD1	Demidov *et al.* (1978)
$^{122}_{52}Te_{70}$	1257/693	2′−2	$-(3.2^{+1.2}_{-0.7})$	RG0	Glaubman (1955)
			−3.52(27)	RG0	Lindgvist (1957)
			−4.1(2)	RG0	Coleman (1958)
			−3.7(2)	RG0	Asplund *et al.* (1960)
			$-(3.0^{+1.0}_{-0.6})$	RG0	Raghavan *et al.* (1965)
			−3.52(8)	RG0	Auerbach *et al.* (1966)
			−3.40(7)	RG0	Johansson *et al.* (1967)
			−3.52(10)	RG0	Koch *et al.* (1967)
			−2.90(25)	RD1	Krane and Steffen (1971)
			−3.48(4)	$r=1.4$	
$^{124}_{52}Te_{72}$	1326/723	2′−2	$-(4.1^{+0.8}_{-0.6})$	RG0	Glaubman and Oberholtzer (1964)
			−3.4(6)	RG1	Stelson (1967)
			$-(3.6^{+1.2}_{-0.8})$	RG0	Sud *et al.* (1970)
			$-(3.6^{+1.5}_{-1.0})$		
			−3.3(1)	RG1	Grabowski *et al.* (1971)
			−3.7(3)	RG2	Grabowski *et al.* (1971)
			−3.6(2)	RG1	Baker *et al.* (1972)
			−3.64(14)	RG1	Sharma *et al.* (1979)
			Ad−3.55(7)		

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
			$-1.00(8)$	RG0	Lindgvist and Marklund (1957)
			$-1.0(2)$	RG0	Paul (1961)
			$-1.0(2)$	RG0	Raghavan *et al.* (1965)
			$-7.5(2.0)$	RD1	Sites and Steyert (1970)
	1958/709	$4'-4$	$0.04^{+0.03}_{-0.05}$	RG2	Grabowski *et al.* (1971)
			$0.02^{+0.06}_{-0.07}$	RG2	Behar *et al.* (1976)
			$0.03^{+0.03}_{-0.04}$		
	2039/1437	$2''-2$	$3.7^{+2.7}_{-1.6}$	RG1	Baker *et al.* (1972)
	2039/714	$2''-2'$	$1.5^{+0.6}_{-0.3}$	RG1	Baker *et al.* (1972)
			$1.5^{+0.5}_{-0.2}$	RG2	Grabowski *et al.* (1971)
			$1.13^{+0.17}_{-0.22}$	RG1	Sharma *et al.* (1979)
			1.30(14)		
	2092/1489	$2'''-2$	$-(3.4^{+1.8}_{-1.0})$	RG1	Baker *et al.* (1972)
$^{126}_{52}Te_{74}$	1421/754	$2'-2$	$-(5.6^{+0.9}_{-0.6})$*	RG0	Sakai *et al.* (1959)
			$-(8.8^{+2.6}_{-1.7})$	RG0	Asplund *et al.* (1960)
			$-(5.5^{+0.4}_{-0.3})$	RG1	Grabowski *et al.* (1971)
			$-(6.0^{+1.6}_{-1.1})$	RG2	Grabowski *et al.* (1971)
			$-(4.3^{+0.5}_{-0.4})$*	RG1	Taylor and Singh (1971)
			$-(5.6^{+0.5}_{-0.4})$	$r=1.6$	
$^{124}_{54}Xe_{70}$	846/492	$2'-2$	$6.3^{+5.3}_{-2.0}$	AD1	Kusakari *et al.* (1975)
			8^{+7}_{-3}	RG1	Singh *et al.* (1979)
			$6.8^{+4.0}_{-1.5}$		
	1248/894	$3-2$	$5.1^{+2.1}_{-1.8}$		
	1248/401	$3-2'$	$1.3^{+1.2}_{-0.6}$		
$^{126}_{54}Xe_{72}$	880/491	$2'-2$	$\lvert\delta\rvert \geq 30$	RG0	Sakai *et al.* (1959)
			27^{+23}_{-9}	RG2	Grabowski *et al.* (1971)
			$10.6^{+2.5}_{-1.7}$	RG1	Taylor and Singh (1971)
			$10.8^{+7.8}_{-3.2}$	AD1	Kusakari *et al.* (1975)
			$12.6^{+3.9}_{-2.6}$	RG1	Sastry *et al.* (1976)
			$13.5^{+3.0}_{-2.0}$	$r=1.8$	
	1317/929	$3-2$	$1.3^{+1.2}_{-0.5}$	AD1	Kusakari *et al.* (1975)
	1317/438	$3-2'$	$10.2^{+6.0}_{-2.5}$ or $0.35^{+0.06}_{-0.03}$		
	1488/546	$4'-4$	$3.0^{+1.1}_{-0.7}$ or $-(0.90^{+0.09}_{-0.08})$		
$^{128}_{54}Xe_{74}$	969/526	$2'-2$	$6.4^{+1.8}_{-1.2}$	RG0	
			$6.4^{+2.7}_{-0.6}$	RG0	Sund *et al.* (1961)
			$6.4^{+0.8}_{-0.6}$	RG0	Hayashi *et al.* (1967)
			$6.4^{+3.4}_{-1.8}$	RG0	Holmberg and Luukko (1967)
			$4.8^{+1.0}_{-0.7}$	RG1	Okano *et al.* (1973)
			6^{+4}_{-2}	RG2	Schneider *et al.* (1979)
			6.1(5)		

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
$^{132}_{54}Xe_{78}$	1298/630	2′−2	$3.2^{+0.9}_{-0.7}$	RG0	Robinson *et al.* (1962)
			$5.7^{+2.1}_{-1.3}$	RG2	Krane and Steffen (1971c)
			8^{+11}_{-3}	RG1	Taylor and Singh (1971)
			2^{+3}_{-2}	RD1	Krane, Olsen, and Steyert (1972)
			$4.8^{+1.2}_{-0.9}$	$r=1.3$	
	1804/1136	3−2	0.9(3)†	RG2	Krane and Steffen (1971c)
	1804/506	3−2′	Ad−1.3(4)	RG2	Krane and Steffen (1971c)
			$-(1.0^{+2.0}_{-0.9})$	RD1	Krane, Olsen, and Steyert (1972)
	1963/523	4′−4	0.07(8)	RG0	Robinson *et al.* (1961)
			$0.03^{+0.09}_{-0.12}$	RG0	Rao (1964)
			Ad−0.25(11)	RG2	Krane and Steffen (1971c)
	1986/1318	2″−2	−0.077(25)	RG0	Robinson *et al.* (1962)
$^{134}_{54}Xe_{80}$	1613/766	2′−2	0.04(6)†	RG1	Gualda *et al.* (1974)
	1920/1073	3−2	0.16(20)		
	2272/540	4′−4	−1.9(1)		
$^{132}_{56}Ba_{76}$	1032/567	2′−2	$\lvert\delta\rvert \geq 14$	RG0	Robinson *et al.* (1962)
			$6.6^{+3.5}_{-1.8}$	RG1	Taylor and Singh (1971)
			$8.3^{+4.9}_{-2.2}$	AD1	Kusakari *et al.* (1975)
			$9.6^{+7.6}_{-2.9}$	$r=1.4$	
	1511/1047	3−2	$2.5^{+0.7}_{-1.0}$ or $0.72^{+0.33}_{-0.12}$	AD1	Kusakari *et al.* (1975)
	1511/479	3−2′	$4.0^{+1.1}_{-1.2}$ or $0.55^{+0.12}_{-0.08}$		
	1730/602	4′−4	$-(1.07^{+0.08}_{-0.20})$ or $6.4^{+9.0}_{-3.7}$		
$^{134}_{56}Ba_{78}$	1168/563	2′−2	$-(7.8^{+7.7}_{-2.5})$	RG2	Behar *et al.* (1972)
			$-(7.5^{+0.9}_{-0.7})$		
			$-(8.1^{+2.8}_{-1.8})$	RG2	Gardulski and Wiedenbeck (1973)
			Ad†$-(7.6^{+0.8}_{-0.6})$		
			$-(12^{+10}_{-4})$	RG0	Stewart *et al.* (1955)
			$-(12.1^{+1.9}_{-1.5})$	RG0	Segaert *et al.* (1963)
			$-(11.3^{+2.7}_{-1.8})$	RG0	Rama Mohan *et al.* (1967)
			8^{+8}_{-3}	RG1	Hofmann *et al.* (1970)
			2.0(4)	RG0	Pande and Singh (1970)
			$\lvert\delta\rvert \geq 21$	RG1	Singh and Taylor (1970a)
			$-(15^{+25}_{-6})$		
			†$13.3^{+2.3}_{-1.8}$	RG2	Ruhter (1977)
			$18^{+8.2}_{-8}$	RG2	
	1643/1038	3−2	2.0(4) or 0.31(8)	RG0	Hsu and Emory (1968)
			0.9(4)*	RG1	Taylor *et al.* (1969)
			0.52(6)	RG1	Hofmann *et al.* (1970)

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
			†1.81(16)	RG2	Behar *et al.* (1972)
			or 0.35(4)		
			†0.82(19)	RG2	Ruhter (1977)
	1643/475	3−2′	$-(15^{+\infty}_{-9})$	RG0	Hsu and Emory (1968)
			$-(12^{+50}_{-6})$	RG1	Hofmann *et al.* (1970)
			$\lvert\delta\rvert \geq 16$	RG2	Behar *et al.* (1972)
			$-(10^{+16}_{-4})$*	RG2	Gardulski and Wiedenbeck (1973)
			$-(17^{+23}_{-6})$		
			−1.1(3)	RG0	Pande and Singh (1970)
	1970/569	4′−4	0.28(2)	RG1	Hofmann *et al.* (1970)
			0.26(3)	RG1	Singh and Taylor (1970a)
			0.29(2)	RG2	Behar *et al.* (1972)
			0.27(2)	RG2	Ruhter (1977)
			0.24(4)		
			0.28(1)		
$^{138}_{56}Ba_{82}$	2308/409	4′−4	$-(0.40^{+0.40}_{-0.30})$	RG1	Singh and Johns (1973b)
			$-(0.05^{+0.20}_{-0.12})$	RG1	Basinger *et al.* (1975)
			$-(0.10^{+0.20}_{-0.10})$		
	2446/1009	3−2	0.008(18)	RG1	Singh and Johns (1973b)
			−0.010(30)	RG1	Basinger *et al.* (1975b)
			0.003(15)		
	2446/547	3−4	−0.04(3)	RG1	Singh and Johns (1973b)
			−0.10(3)	RG1	Basinger *et al.* (1975b)
			−0.07(2)		
$^{140}_{56}Ba_{84}$	1511/908	2′−2	$-(1.10^{+0.14}_{-0.10})$	RG1	Alquist *et al.* (1976)
	1951/820	3−4	$-(1.0^{+1.4}_{-0.5})$		
	1994/1391	2″−2	0.16(6)		
$^{140}_{58}Ce_{82}$	2348/752	2′−2	0.33(3)	RG1	Wiedenbeck and Raeside (1971)
			0.37(6)	RG1	Saxena and Sharma (1973)
			0.35(4)	RG1	Roehmer (1973)
			0.34(2)		
	2412/816	3−2	−0.035(17)*	RG0	Black and Mitchell (1963)
			−0.031(5)	RG1	Wiedenbeck and Raeside (1971)
			−0.033(8)	RG1	Saxena and Sharma (1973)
			−0.03(2)	RG1	Roehmer (1973)
			−0.034(13)	RG1	Avramov *et al.* (1975)
			−0.029(8)	RG1	Garcia-Bermudez *et al.* (1976)
			−0.031(4)		
			$\lvert\delta\rvert \geq 0.02$	RG0	Bishop *et al.* (1955)
			0.15(1)*	RG0	Bolotin *et al.* (1955)
			0.08(1)	RG0	Kelly *et al.* (1956)
			−0.11(5)	RD0	Blok and Shirley (1966)
	2412/329	3−4†	−0.043(18)	RG0	Black and Mitchell (1963)

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
			$-0.039(12)$	RG0	Dorikens-Vanpraet *et al.* (1963)
			$-0.042(4)$	RG0	Körner *et al.* (1963)
			$-0.044(7)$	RG0	Letessier *et al.* (1970)
			$-0.019(7)$	RG1	Wiedenbeck and Raeside (1971)
			$-0.057(24)$*	RG1	Saxena and Sharma (1973)
			$-0.055(23)$*	RG1	Avramov *et al.* (1975)
			$-0.039(4)$	$r=1.3$	
			$0.061(16)$	RG0	Dorikens-Vanpraet *et al.* (1963)
	2516/432	$4'-4$	$-0.06\geq\delta\geq 0.84$	RG1	Saxena and Sharma (1973)
			$-(0.07^{+0.20}_{-0.13})$*		
			$0.05\geq\delta\geq -1.06$	RG1	Avramov *et al.* (1975)
			$-0.24\geq\delta\geq -0.59$	RG1	Garcia-Bermudez *et al.* (1976)
			$-0.20\geq\delta\geq -0.63$		
			$-0.03(4)$	RG0	Cords (1969)
			$-0.36^{\dagger}$	RG1	Wiedenbeck and Raeside (1971)
	2522/925	$2''-2^{\dagger}$	$-0.13(7)$	RG1	Saxena and Sharma (1973)
			Ad $-0.15(3)$	RG1	Roehmer (1973)
$^{142}_{58}Ce_{84}$	1536/895	$2'-2^{\dagger}$	$-0.09(3)$	RG0	Prestwich and Kennett (1965)
			$-(0.28^{+0.29}_{-0.13})$*	RG1	Basinger *et al.* (1975a)
			$-0.10(5)$	$r=1.5$	
$^{144}_{60}Nd_{84}$	1561/865	$2'-2^{\dagger}$	$-1.6(5)$	RG1	Behar *et al.* (1974)
	2085/1389	$2''-2$	$-(1.81^{+0.24}_{-0.21})$		
$^{146}_{60}Nd_{86}$	1471/1017	$2'-2$	13^{+19}_{-8}	RG1	Ikeda *et al.* (1978)
	1778/1324	$3-2$	$-(5^{+60}_{-3})$	RG1	
	1788/1334	$2'-2$	$-(1.4^{+1.0}_{-0.8})$	RG1	
	1906/1452	$2''-2$	$-(0.68^{+0.56}_{-0.42})$	RG1	
$^{150}_{62}Sm^{\dagger}_{88}$	1046/712	$2,0-2g$	$-(6.8^{+5.4}_{-2.1})$	RG0	Smither (1966)
			$\delta\leq -0.4$		
			$-(4.4^{+0.6}_{-0.5})$	RG1	Kalfas *et al.* (1975)
			$-(5.8^{+2.0}_{-1.2})$	RG1	Hoshi *et al.* (1977)
			$-(4.7^{+1.2}_{-0.8})$	RG1	Hoshi *et al.* (1977)
			$-(4.8^{+0.5}_{-0.4})$		
	1449/676	$4,0-4g$	$-1.5(3)$*	RG0	Cojocaru *et al.* (1966)
			$-0.4>\delta>-1.3$	RG0	Smither (1966)
			$-1.3(3)$		
	1194/860	$2,2-2g$	$3.4^{+0.9}_{-0.7}$	RG1	Kalfas *et al.* (1975)
			$3.4^{+1.6}_{-1.0}$	RG1	Hoshi *et al.* (1977)
			$3.4^{+0.8}_{-0.6}$		
	1505/1171	$3,2-2g$	$3.6^{+1.7}_{-1.0}$	RG1	Kalfas *et al.* (1975)
	1505/731	$3,2-4g$	$13^{+\infty}_{-7}$	RG0	Smither (1966)
	1643/869	$4,2-4g$	$\delta\geq 0.7$	RG0	Smither (1966)
	1279/506	$3,K-4g$	$-2.3(4)$	RG0	Smither (1966)

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
$^{152}_{62}Sm_{90}$	1087/965	2,2−2g	$-(13.3^{+7.2}_{-3.4})$	RG0	Ofer (1957)
			$-(7.7^{+4.0}_{-2.0})$	RG0	Lide and Wiedenbeck (1959)
			$-(6.1^{+1.9}_{-1.2})$	RG0	Debrunner and Kundig (1960)
			$-(18^{+22}_{-7})$	RG0	Aquili *et al.* (1969)
			$-(27^{+55}_{-11})$	AP1	Fraser *et al.* (1969)
			$-(8.1^{+0.5}_{-0.4})$	RG2	Barrette *et al.* (1970)
			$-(15.8^{+3.1}_{-2.2})$	RG1	Helppi and Hattula (1970)
			−9.2(2)	RP1	Ramayya *et al.* (1970)
			$-(10.8^{+5.8}_{-2.8})$	RP0	Rud and Nielsen (1970)
			$-(12.2^{+2.4}_{-1.7})$	RG0	
			$-(13.5^{+4.5}_{-2.7})$	RG0	Lange *et al.* (1971)
			$-(11.6^{+7.4}_{-3.2})$	RG0	
			$-(11.0^{+0.9}_{-0.8})$	RG2	
			−10.2(8)	RG1	Kalfas *et al.* (1973)
			$-(11.3^{+0.9}_{-0.7})$		
			$-(23^{+\infty}_{-15})$	AD1	Domingos *et al.* (1974)
			−9.6(3)	$r=1.7$	
			−3.8(1.8)	AD1	McGowan (1972)
			−4.0(34)	RD1	Barclay and Perczuk (1975)
	1235/1113	3,2−2g	$-(17^{+\infty}_{-10})$	RG0	Debrunner and Kundig (1960)
			$-(20.4^{+4.7}_{-3.2})$	RG0	Aquili *et al.* (1969)
			$-(13.7^{+3.1}_{-2.1})$	RG2	Barrette *et al.* (1970)
			$-(15.4^{+2.6}_{-1.9})$	RG1	Helppi and Hattula (1970)
			$-(16.8^{+3.6}_{-2.5})$	RP1	Ramayya *et al.* (1970)
			$-(26^{+8}_{-5})$	RG1	Kalfas *et al.* (1973)
			$-(30^{+13}_{-7})$		
			$-(19.4^{+2.5}_{-2.0})$	$r=1.4$	
			$-(6.6^{+6.6}_{-2.4})$	RP0	Rud and Nielsen (1970)
			$-(8.8^{+1.2}_{-0.9})$	RG1	
			$-(8.8^{+3.2}_{-1.9})$	RG0	Lange *et al.* (1971)
			$-(8.6^{+0.9}_{-0.7})$	RG2	
			$-(9^{+\infty}_{-6})$	RD1	Barclay and Perczuk (1975)
			Ad[†] −8.7(6)		
			12^{+20}_{-5}	RG0	Ofer (1957)
			22^{+55}_{-9}	RG0	Lide and Wiedenbeck (1959)
	1235/869	3,2−4g	$-(6.6^{+2.8}_{-1.6})$	RG0	Lide and Wiedenbeck (1959)
			$-(9.1^{+1.8}_{-1.3})$	RP0	Nathan (1960)
			$-(6.2^{+0.8}_{-0.7})$	RP0	Bisgard *et al.* (1963)
			$-(7.1^{+1.2}_{-0.9})$	RG2	Barrette *et al.* (1970)
			$-(8^{+13}_{-3})$	RG1	Helppi and Hattula (1970)
			−5.6(4)		
			$-(5.0^{+0.9}_{-0.6})$	RG2	Lange (1970b)
			−6.1(3)	RP1	Ramayya *et al.* (1970)
			$-(7.6^{+1.1}_{-0.9})$	RG1	Rud and Nielsen (1970)
			$-(8.2^{+1.5}_{-1.2})$	RP0	
			$-(8.9^{+2.4}_{-1.5})$	RG0	
			$-(6.4^{+0.6}_{-0.4})$	RG2	Barrette *et al.* (1971)
			−6.5(3)	$r=1.5$	
			$-(12.3^{+4.0}_{-2.5})$	RG1	Kalfas *et al.* (1973)
			$-(12.1^{+1.7}_{-1.2})$		

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
	1372/1005	4,2−4*g*	$-(3.0^{+2.0}_{-0.9})$	RG2	Barrette *et al.* (1970)
			$-(4.5^{+2.5}_{-1.2})$	RG1	Helppi and Hattula (1970)
			$-(5^{+17}_{-2})$	RG2	Lange (1970b)
			$-(2.8^{+0.3}_{-0.2})$	RP1	Ramayya *et al.* (1970)
			$-(3.3^{+0.5}_{-0.4})$	RG2	Barrette *et al.* (1971)
			$-(2.8^{+2.3}_{-0.9})$	RG1	Kalfas *et al.* (1973)
			$-(3.1^{+0.3}_{-0.2})$		
			$-(13^{+\infty}_{-8})$	AP1	Fraser *et al.* (1969)
			$\lvert\delta\rvert \geq 10$	AD1	Domingos *et al.* (1974)
	811/689	2,0−2*g*	$\lvert\delta\rvert \geq 11$*	RG0	Aquili *et al.* (1969)
			$67^{+\infty}_{-54}$	AP1	Fraser *et al.* (1969)
			$\lvert\delta\rvert \geq 24$	RG2	Barrette *et al.* (1970)
			$\lvert\delta\rvert \geq 16$*	RG1	Helppi and Hattula (1970)
			17^{+6}_{-3}	RP1	Ramayya *et al.* (1970)
			$15^{+\infty}_{-9}$	RG1	Rud *et al.* (1971)
			13^{+28}_{-5}	AD1	McGowan (1972)
			8^{+8}_{-3}	RG1	Kalfas *et al.* (1973)
			8^{+6}_{-3}	AP1	Domingos *et al.* (1974)
			19^{+5}_{-4}		
	1023/657	4,0−4*g*	$2.9^{+1.9}_{-0.9}$	AP1	Fraser *et al.* (1969)
			$3.1^{+1.5}_{-1.4}$	RP1	Ramayya *et al.* (1970)
			$8^{+\infty}_{-7}$	RG2	Barrette *et al.* (1971)
			Ad 2.1(3)	AP1	Domingos *et al.* (1974)
$^{150}_{64}Gd_{86}$	1431/793	2′−2	2.0(7)	RD1	Hamilton *et al.* (1978)
	1519/860	2″−2	7^{+3}_{-1}	RD1	
	1700/412	4′−4	−0.20(13)	RD1	
	1956/525	2‴−2′	$0.19^{+0.26}_{-0.15}$	RD1	
$^{152}_{64}Gd_{88}$	931/586	2,0−2*g*	$-(2.0^{+0.5}_{-0.4})$	RG2	Barrette *et al.* (1970)
			−3.05(14)	RG1	Kalfas *et al.* (1972)
			−3.0(3)	$R=2.0$	
	1109/765	2,2−2*g*	Ad $4.3^{+0.7}_{-0.6}$	RG1	Kalfas *et al.* (1972)
			$3.4^{+2.6}_{-1.0}$	RD1	
	1318/974	2,0−2*g*	Ad 0.58(7)	RG1	
			$0.4 \leq \delta \leq 1.0$	RD1	
	1434/1090	3,2−2*g*	21^{+22}_{-7}	RG0	Grabowski (1971)
			28^{+36}_{-10}	RG2	Helppi *et al.* (1975)
			Ad† 25^{+15}_{-7}		
			−0.17(2)	RG0	Schick and Grodzins (1965)
			−0.22(3)	RG2	Barrette *et al.* (1970)
			−0.19(3)	$r=1.7$	
	1434/679	3,2−4*g*	$\lvert\delta\rvert \geq 24$	RG0	Schick and Grodzins (1965)
			$\lvert\delta\rvert \geq 9$	RG2	Barrette *et al.* (1970)
			$-(42^{+\infty}_{-21})$	RG2	Helppi *et al.* (1975)
			$\lvert\delta\rvert \geq 14$*		
			$-(85^{+\infty}_{-53})$		
	1941/623	2,2−2,0	$0.3 \leq \delta \leq 2.9$	RG1	Kalfas *et al.* (1972)
			$0.2 \leq \delta \leq 1.5$	RD1	

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
$^{154}_{64}Gd_{90}$	996/873	2,2−2g	$-(6.6^{+7.4}_{-2.3})$	RG0	Debrunner and Kundig (1960)
			$-(10.2^{+2.7}_{-1.8})$	RG0	Varnell *et al.* (1969)
			$-(7.9^{+1.7}_{-1.2})$	RG0	Rud and Nielsen (1970)
			$-(7.9^{+1.1}_{-0.9})$	RP0	
			$-(7.5^{+1.8}_{-1.3})$	RG1	
			$-(10.7^{+6.5}_{-2.9})$*	RG0	Lange *et al.* (1971)
			$-(9.8^{+1.5}_{-1.2})$	RG0	
			$-(10.8^{+2.5}_{-1.7})$	RG2	
			$-(11.7^{+3.2}_{-2.1})$	RG1	Whitlock *et al.* (1971)
			$-(8.0^{+2.2}_{-1.3})$		
			$-(10.7^{+3.3}_{-2.0})$	RG2	Gottel *et al.* (1972)
			$-(13.3^{+7.1}_{-3.4})$		
			$-(10.0^{+4.0}_{-2.2})$	RG1	Ober *et al.* (1973)
			$-(9.4^{+0.8}_{-0.6})$	RG1	Gupta *et al.* (1977)
			−9.7(5)		
			$-(4.2^{+2.6}_{-1.4})$	RG0	Hickman and Wiedenbeck (1958)
			$-(30^{+\infty}_{-17})$	RG0	Debrunner and Kundig (1960)
			$-(5.0^{+1.6}_{-1.1})$	RG0	Varnell *et al.* (1969)
	1128/1005	3,2−2g	$-(18^{+10}_{-5})$	RG0	Hickman and Wiedenbeck (1958)
			$34^{+\infty}_{-27}$	RG0	Debrunner and Kunkig (1960)
			$\lvert\delta\rvert \geq 30$	RG0	Varnell *et al.* (1969)
			$-(22^{+24}_{-7})$	RG1	Whitlock *et al.* (1971)
			$-(18^{+10}_{-5})$	RG2	Gottel *et al.* (1972)
			$-(26^{+11}_{-6})$		
			$-(8.3^{+1.4}_{-1.1})$	RG0	Rud and Nielsen (1970)
			$-(9.0^{+2.4}_{-1.6})$	RP0	
			$-(8.1^{+1.6}_{-1.1})$	RG1	
			$-(8.8^{+4.5}_{-2.3})$	RG0	Lange *et al.* (1971)
			−6.6(7)	RG2	
			$-(9.5^{+7.0}_{-4.0})$	RG1	Ober *et al.* (1973)
			−7.7(7)*	RG1	Gupta *et al.* (1977)
			$-(6.0^{+1.6}_{-1.1})$	AD1	West *et al.* (1978)
			Ad† −7.5(4)		
	1128/757	3,2−4g	−4.9(5)	RG0	Varnell *et al.* (1969)
			−5.9(7)	RP0	Rud and Nielsen (1970)
			$-(6.0^{+1.0}_{-0.8})$	RG1	
			−5.6(2)	RG1	Whitlock *et al.* (1971)
			−4.7(7)	RG2	Gottel *et al.* (1972)
			$-(5.0^{+1.7}_{-1.1})$		
			−6.1(4)*	RG1	Gupta *et al.* (1977)
			$-(6.0^{+1.6}_{-1.1})$	AD1	West *et al.* (1978)
			−5.6(2)		
	1264/893	4,2−4g	$-(3.0^{+0.8}_{-0.5})$	RG0	Varnell *et al.* (1969)
			$-(4.3^{+0.7}_{-0.4})$	RG1	Whitlock *et al.* (1971)
			$-(4.3^{+2.3}_{-1.1})$*	RG1	Collins and Hamilton (1973)
			$-(4.0^{+0.8}_{-0.5})$*	RG1	Gupta *et al.* (1977)
			$-(2^{+12}_{-1})$	AD1	West *et al.* (1978)
			−4.1(4)		
	816/692	2,0−2g	10^{+11}_{-4}	RG1	Rud and Nielsen (1970)
			$10.1^{+5.1}_{-2.6}$	RG1	Whitlock *et al.* (1971)
			$7.7^{+1.5}_{-1.1}$	RG1	Gupta *et al.* (1977)
			$8.3^{+1.5}_{-1.1}$		

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
	1048/677	4,0−4*g*	$1.3 \leq \delta \leq 8.8$	RG1	Whitlock *et al.* (1971)
			$2.1 \leq \delta \leq 3.0$	RG1	Collins and Hamilton (1973)
			$1.4 \leq \delta \leq 6.3$	RG1	Gupta *et al.* (1977)
			$2.9^{+2.1}_{-0.9}$	AD1	West *et al.* (1978)
			$1.7 \leq \delta \leq 4.3^{\dagger}$		
	1366/648	6,0−6*g*	$3.5^{+2.5}_{-2.0}$	AD1	Ferguson *et al.* (1970)
			$1.8^{+0.3\dagger}_{-0.2}$	AD1	Ward *et al.* (1973), Gono and Gugihara (1974)
			$1.30^{+0.21}_{-0.18}$	AD1	West *et al.* (1978)
			$1.55^{+0.18}_{-0.14}$		
	1757/612	8,0−8*g*	$1.0^{+0.7}_{-0.6}$	AD1	Ferguson *et al.* (1970)
			Ad $1.2^{+0.4\dagger}_{-0.3}$	AD1	Ward *et al.* (1973), Gono and Sugihara (1974)
			$-(0.69^{+0.14}_{-0.12})$	AD1	West *et al.* (1978)
	2194/438	10,0−10*g*	$1.1^{+0.5\dagger}_{-0.3}$	AD1	Ward *et al.* (1973), Gono and Sugihara (1974)
$^{156}_{64}Gd_{92}$	1154/1065	2,2−2*g*	$\lvert\delta\rvert \geq 5$	RG1	Kenealy *et al.* (1967)
			$\lvert\delta\rvert \geq 2$		
			$-(18^{+17}_{-6})$	RG1	Rud and Nielsen (1970)
			$-(18.0^{+3.0}_{-2.2})$	RG1	Hamilton *et al.* (1972)
			$-(10^{+45}_{-5})$	RD1	Uluer *et al.* (1975)
			$\lvert\delta\rvert \geq 4$	RG1	
			$-(17.2^{+2.2}_{-1.7})$	RG1	Collins *et al.* (1977)
			$-(17.5^{+1.6}_{-1.4})$		
	1249/1159	3,2−2*g*	$-(10^{+\infty}_{-5})$	RG1	Kenealy *et al.* (1967)
			$10^{+100.}_{-1.4}$	RD1	Uluer *et al.* (1975)
			Ad $-(8.6^{+4.8}_{-2.3})$	AD1	Rikovska *et al.* (1979)
	1249/960	3,2−4*g*	5^{+20}_{-3}	RG1	Kenealy *et al.* (1967)
			$-(12^{+14}_{-3})$	RD1,RG1	Uluer *et al.* (1975)
	1356/1067	4,2−4*g*	$\lvert\delta\rvert \geq 3$	RG1	Kenealy *et al.* (1967)
			Ad$-(4.0^{+1.6}_{-0.9})$	RG1	Uluer *et al.* (1975)
	1129/1040	2,0−2*g*	$-(5.9^{+2.8}_{-1.4})$	RG1	Hamilton *et al.* (1972)
			$\lvert\delta\rvert \geq 28$	RG1	Collins *et al.* (1977)
			$-(14^{+\infty}_{-7})$	$r=2.2$	
	1258/1169	2,0−2*g*	0.39(6)	RG1	Collins *et al.* (1977)
$^{158}_{64}Gd_{94}$	1188/1108	2,2−2*g*	$-(23^{+\infty}_{-14})$	RG0	Schroeer and Jastram (1968)
$^{160}_{66}Dy_{94}$	966/879	2,2−2*g*†	$-(7.0^{+4.7}_{-2.1})$	RG0	Arns *et al.* (1959)
			$-(23^{+\infty}_{-11})$	RG0	Simons *et al.* (1962)
			$-(7.8^{+4.8}_{-2.3})$	RG0	Michaelis (1963)
			$-(14.8^{+3.9}_{-2.5})$	RG0	Gunther *et al.* (1965)
			$-(22.2^{+4.8}_{-3.3})$		
			$-(22.9^{+4.4}_{-3.2})$		
			$-(7.3^{+3.8}_{-2.0})$	RG0	Gupta and Saha (1965)
			$-(7.0^{+3.2}_{-1.7})$	RG0	Reddy *et al.* (1965a)

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
			$-(13.3^{+3.9}_{-2.4})$	RG1	Jaklevic *et al.* (1967)
			$-(16.3^{+14.9}_{-5.4})$		
			$-(15.8^{+8.2}_{-4.1})$	RG2	Krane and Steffen (1971b)
			$-(9.6^{+2.6}_{-1.6})$		
			$-(16.1^{+1.5}_{-1.3})$	RG2	Gardulski and Wiedenbeck (1973)
			$-(16.3^{+3.4}_{-2.5})$		
			−15(2)	RG1	Bhati *et al.* (1976)
			−12.8(15)	AD1	Gromova *et al.* (1979)
			−14.8(11)	$r=1.4$	
			$49^{+\infty}_{-23}$	RG0	Ofer (1958)
			$-(6.1^{+2.3}_{-1.4})$	RD0	Johnson *et al.* (1960)
			$47^{+\infty}_{-31}$*	RG0	Reddy *et al.* (1965a)
			$-(18^{+8}_{-4})$	RD1	Fox *et al.* (1974)
	1049/692	3,2−2*g*	$-(18^{+20}_{-6})$	RG1	Jaklevic *et al.* (1967)
			$-(9^{+3}_{-2})$	RG2	Lange (1970b)
			$-(16^{+\infty}_{-9})$	RG2	Krane and Steffen (1971b)
			$-(18^{-\infty}_{-9})$		
			$-(8.4^{+2.7}_{-1.7})$	RG1	Bhati *et al.* (1976)
			−6.5(5)	RG1	
			$-7.2(5)^{\dagger}$		
			6.5(45)	AD1	Gromova *et al.* (1979)
	1049/765	3,2−4*g*	$-(4.7^{+5.0}_{-1.7})$	RG2	Lange (1970b)
			$-(7^{+35}_{-4})$	RG2	Krane and Steffen (1971b)
			$-(9.0^{+5.0}_{-2.4})$	AD1	Gromova *et al.* (1979)
			$-(6.8^{+3.6}_{-1.4})$		
			$-(7.7^{+0.7}_{-0.6})^{\dagger}$	RD1	Fox *et al.* (1974)
$^{162}_{66}Dy_{96}$	888/808	2,2−2*g*	$-(7^{+\infty}_{-6})$	AD1	Engler and Lane (1970)
			$80^{+\infty}_{-60}$	AP1	Domingos *et al.* (1972)
			$-(8^{+\infty}_{-5})$	AD1	Hooper *et al.* (1977)
			$\lvert\delta\rvert \geq 20$		
	963/882	3,2−2*g*	Ad$-(19^{+\infty}_{-13})$ or 0.21(11)	AD1	Hooper *et al.* (1977)
	1061/795	4,2−4*g*	Ad$-1.3 \leq \delta \leq 8.5$*	AP1	Domingos *et al.* (1972)
			$\delta \geq 2.0$ or $\delta \leq -0.4$	AD1	Hooper *et al.* (1977)
	1183/918	5,2−4*g*	$-(7^{+\infty}_{-5})$	AD1	Hooper *et al.* (1977)
$^{164}_{66}Dy_{98}$	762/689	2,2−2*g*	$-(8^{+\infty}_{-6})$ or $(0.6^{+1.5}_{-0.2})$	AD1	Engler and Lane (1970)
			$-(6^{+\infty}_{-4})$ or $-(0.7^{+0.5}_{-0.4})$	AD1	Hooper *et al.* (1977)
			Ad$-(7^{+\infty}_{-4})$ or $-(0.6^{+0.3}_{-0.2})$		
	828/755	3,2−2*g*	Ad$-(29^{+\infty}_{-23})$ or 0.23(13)	AD1	Hooper *et al.* (1977)

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
	916/674	4,2 − 4g	Ad $2.7^{+\infty}_{-1.3}$ or $-(0.5^{+0.4}_{-0.3})$		
	1025/783	5,2 − 4g	Ad $5.1^{+\infty}_{-2.5}$ or $0.4^{+0.3}_{-0.2}$		
$^{162}_{68}Er_{94}$	1002/673	3,2 − 4g	Ad $-(6.6^{+\infty}_{-4.4})$ or $-(0.04^{+0.17}_{-0.27})$	AD1	West *et al.* (1976)
	1286/957	5,2 − 4g	$-(7.9^{+10.1}_{-3.8})$		
	1286/620	5,2 − 6g	$0.00^{+0.16}_{-0.10}$		
	1460/793	6,2 − 6g	$\delta \geq 18$ or $-(3.5^{+5.5}_{-2.2})^{\dagger}$		
	1460/173	6,2 − 5,2	$2.65^{+1.45}_{-0.75}$ or $0.48^{+0.28}_{-0.15}$		
	1670/1003	7,2 − 6g	$-(7.9^{+7.1}_{-3.3})$		
$^{164}_{68}Er_{96}$	948/854	3,2 − 2g	Ad $-(7.7^{+\infty}_{-5.1})$ or $0.13^{+0.26}_{-0.25}$	AD1	West *et al.* (1976)
	1059/759	4,2 − 4g	$\delta \geq 7$ or $-(1.15^{+1.02}_{-0.35})$		
	1197/898	5,2 − 4g	$-(4.8^{+5.9}_{-1.5})$ or $0.00^{+0.07}_{-0.14}$		
	1197/583	5,2 − 6g	$12.0^{+\infty}_{-6.8}$ or $0.02^{+1.11}_{-0.02}$		
	1358/744	6,2 − 6g	$\delta \geq 3.3$ or $-(1.9^{+1.0}_{-1.6})$		
	1545/931	7,2 − 6g	$-(6.5^{+5.5}_{-2.2})$		
	1744/720	8,2 − 8g	$12.0^{+\infty}_{-6.8}$ or $-(1.5^{+3.0}_{-0.8})$		
$^{166}_{68}Er_{98}$	786/705	2,2 − 2g	$-(16^{+\infty}_{-8})$ $-(16^{+15}_{-6})$ $-(16^{+13}_{-5})$	AP1	Domingos *et al.* (1972)
			$\delta \leq -25$	AD1	McGowan *et al.* (1978)
	859/779	3,2 − 2g	$-(19^{+\infty}_{-10})$	RG2	Baker *et al.* (1975)
			$-(20^{+\infty}_{-13})$ $-(19^{+190}_{-9})$	AD1	West *et al.* (1976)
			$\lvert\delta\rvert \geq 10$	RG0	Bozek *et al.* (1961)
	359/593	3,2 − 4g	$\lvert\delta\rvert \geq 2$ Ad $-(9^{+\infty}_{-5})$	RG2 RG1	Baker *et al.* (1975)
	956/691	4,2 − 4g	$7.5^{+\infty}_{-1.5}$ $-(10^{+27}_{-4})$ $-(16^{+27}_{-4})$	RG2 RG1	Baker *et al.* (1975)

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
			$-19 \leq \delta \leq -1$*	AP1	Domingos *et al.* (1972)
	1075/810†	5,2−4g	$\lvert\delta\rvert \geq 11$*	RG0	Grace *et al.* (1958)
			$-(26^{+11}_{-5})$	RD0	Postma *et al.* (1959)
			$16^{+\infty}_{-8}$*	RG0	Gerdau *et al.* (1963)
			$-(11^{+20}_{-5})$		
			$-(37^{+68}_{-15})$*	RG0	Reich and Cline (1965)
			$-(19^{+15}_{-6})$		
			$-(16.2^{+3.3}_{-2.4})$	RG1	
			$-(20.1^{+3.6}_{-2.6})$	RG2	Baker *et al.* (1975)
			$-(25^{+33}_{-10})$	RG1	
			$-(84^{+\infty}_{-57})$	AD1	West *et al.* (1976)
			$-(21.6^{+2.5}_{-2.1})$		
	1075/530	5,2−6g	$-(86^{+\infty}_{-44})$	RG0	Reich and Cline (1965)
			$-(27^{+5}_{-4})$	RG2	Baker *et al.* (1975)
			$-(17^{+48}_{-7})$	RG1	
			$-(14^{+5}_{-4})$	RG2	
			$-(27^{+8}_{-5})$	$r=1.7$	
			$-5.0(2.5)$†	AD1	West *et al.* (1976)
	1216/671	6,2−6g	$-(15^{+\infty}_{-8})$	RG2	Baker *et al.* (1975)
			$-(37^{+\infty}_{-26})$	RG1	
			$-(16^{+\infty}_{-8})$	RG2	
			$-(20^{+90}_{-9})$		
			$6.3^{+\infty}_{-2.9}$†	AD1	West *et al.* (1976)
	1376/831	7,2−6g	$-(71^{+\infty}_{-31})$	RG0	Reich and Cline (1965)
			$-(43^{+37}_{-14})$	RG1	
			$-(15^{+12}_{-4})$	RG2	Baker *et al.* (1975)
			$-(19^{+16}_{-6})$	RG1	
			$-(23^{+11}_{-6})$	RG2	
			$-(37^{+\infty}_{-17})$	AD1	West *et al.* (1976)
			$-(35^{+9}_{-6})$		
			$-(5.9^{+1.3}_{-0.9})$	RG0	Gerdau *et al.* (1963)
	1376/465	7,2−8g	$-(13^{+150}_{-7})$	RG1	Baker *et al.* (1975)
			$-(22^{+53}_{-7})$	RG2	
			$\lvert\delta\rvert \geq 25$		
			$-(32^{+98}_{-14})$		
			$-(3.1^{+1.5}_{-0.9})$	AD1	West *et al.* (1976)
	1556/645	8,2−8g†	$\delta \geq 1.4$* or $\delta \leq -6$*	RG2	Baker *et al.* (1975)
$^{168}_{68}Er_{100}$	821/741	2,2−2g	$22^{+\infty}_{-16}$	RG0	Reidy *et al.* (1964)

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
			$65^{+\infty}_{-26}$	RG0	Lange *et al.* (1971)
			$-(53^{+\infty}_{-34})$	AP1	Domingos *et al.* (1972)
			$23^{+\infty}_{-17}$	RG2	Baker *et al.* (1975)
			$-(28^{+23}_{-9})$		
			$\lvert\delta\rvert \geq 87$	$r=1.3$	
			$\delta \leq -25$	AD1	McGowan *et al.* (1978)
	896/816	3,2−2*g*	$\lvert\delta\rvert \geq 7$	RG0	Reidy *et al.* (1964)
			$-(60^{+\infty}_{-30})$	RP0	Hasselgren *et al.* (1971)
			$18^{+2.7}_{-0.7}$	RG1	Abdurazakov *et al.* (1975)
			$16.8^{+3.2}_{-2.5}$	RG2	Behar *et al.* (1975)
			$17.4^{+2.1}_{-0.8}$		
	896/632	3,2−4*g*	37^{+11}_{-7}	RP0	Hasselgren *et al.* (1971)
			$60^{+\infty}_{-35}$	RG1	Abdurazakov *et al.* (1975)
			$-(10^{+\infty}_{-5})$		
			Ad −4.9(3)	RG2	Behar *et al.* (1975)
	995/731	4,2−4*g*	$-(18^{+29}_{-7})$	RP0	Hasselgren *et al.* (1971)
			$-(5^{+10}_{-4})$	AP1	Domingos *et al.* (1972)
			$25^{+\infty}_{-13}$	RG2	Behar *et al.* (1975)
			$50^{+\infty}_{-33}$		
			$-(100^{+\infty}_{-60})$		
$^{170}_{68}Er_{102}$	932/853	2,2−2*g*	Ad $-(55^{+\infty}_{-34})$	AP1	Domingos *et al.* (1972)
			$\delta \leq -70$	AD1	McGowan *et al.* (1978)
	960/881	2,0−2*g*	1.7(8)		
	1101/840	4,2−4*g*	$\lvert\delta\rvert \geq 8$	AP1	Domingos *et al.* (1972)
	1124/863	4,0−2*g*	$-(5^{+\infty}_{-3})$		
	1332/398	2,*K*−2,2	$-(0.40^{+0.20}_{-0.15})$	AD1	McGowan *et al.* (1978)
$^{172}_{70}Yb_{102}$	1466/1387	2,2−2*g*	$-(9.3^{+5.0}_{-2.5})$	RG2	Lange (1970b)
			$-(2.4^{+0.8}_{-1.5})$	RD1	Krane *et al.* (1976)
			$-(4.4^{+4.5}_{-1.9})^{\dagger}$		
	1549/1470	3,2−2*g*	$-(5.6^{+3.0}_{-2.0})$	RG2	Lange (1970b)
			$-(7.6^{+1.4}_{-1.0})$	RD1	Krane *et al.* (1976)
			$-(7.2^{+1.3}_{-0.9})$		
	1477/1398	2,2′−2*g*	$\delta \geq 2.2$ or $0.40 \leq \delta \leq 1.25$	RG2	Lange (1970b)
	1609/1530	2,2″−2*g*	$8.0^{+2.0}_{-1.5}$		
	1701/1622	3,2″−2*g*	18^{+5}_{-3} or 0.31(1)	RD1	Krane *et al.* (1976)
	1701/1441	3,2″−4*g*	10^{+4}_{-3}		
	1803/1543	4,2″−4*g*	$-(22^{+\infty}_{-13})$ or −1.2(2)		
	1927/1666	5,2″−4*g*	$-(6.1^{+1.2}_{-0.9})$ or 0.33(3)		
$^{174}_{72}Hf_{102}$	901/809	2,0−2*g*	$-(11^{+\infty}_{-7})$	AD1	
	1063/765	4,0−4*g*	$-(2.5^{+1.3}_{-0.7})$		
	1308/699	6,0−6*g*	−0.9(2)		
$^{176}_{72}Hf_{104}$	1227/1138	2,0−2*g*	$\lvert\delta\rvert \geq 4$	AD1	Hammer *et al.* (1973)
	1391/1101	4,0−4*g*	$\lvert\delta\rvert \geq 0.7$		
$^{178}_{72}Hf_{106}$	1175/1082	2,2−2*g*	$\lvert\delta\rvert \geq 11$	AD1	Varnell *et al.* (1971)

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
			$\|\delta\| \geq 2$	RG1	Little *et al.* (1972)
	1277/1183	2,0−2*g*	$0.41^{+0.09}_{-0.07}$	RG0	Nielson *et al.* (1968)
			Ad 0.410(36)	RG1	Little *et al.* (1972)
	1496/1403	2,0−2*g*†	$-0.77^{+0.50}_{-0.40}$*	RG0	Nielson *et al.* (1968)
			Ad $-0.75^{+0.19}_{-0.17}$*	RG1	Little *et al.* (1972)
$^{180}_{72}Hf_{108}$	1201/1107	2,2−2*g*	Ad $9.6^{+22}_{-5.8}$ or 0.7(2)	AD1	Varnell *et al.* (1974)
$^{182}_{74}W$	1222/1122	2,2−2	6^{+6}_{-2}	RG0	Hickman and Wiedenbeck (1960)
			$11.3^{+3.8}_{-2.3}$	RG0	El-Nesr *et al.* (1963)
			17^{+36}_{-7}	AD1	Milner *et al.* (1971)
			21^{+19}_{-6}	RD1	Krane, Sites and Steyert (1972b)
			24^{+21}_{-8}	RG2	Herzog *et al.* (1972)
			$16.7^{+4.1}_{-2.7}$		
			$-2.6^{+3.0}_{-1.9}$	RG0	Wiedling (1956)
			−5.0(5)	RG0	El-Nesr *et al.* (1963)
	1257/1157	2″−2	$-(9^{+6}_{-3})$	AD1	Milner *et al.* (1971)
			$-(8^{+\infty}_{-5})$	RD1	Krane, Sites, and Steyert (1972b)
			$-(8.7^{+5.5}_{-2.5})$		
			$-1.60 \leq \delta \leq -0.65$	RG2	Herzog *et al.* (1972)
	1331/1231	3,2−2	$-(60^{+100}_{-20})$	RD1	Krane, Sites, and Steyert (1972b)
	1331/1002	3,2−4	$-(8.9^{+2.1}_{-1.8})$		
	1442/1113	4,2−4	$-(20^{+\infty}_{-13})$	RG0	Westerberg *et al.* (1975)
$^{184}_{74}W_{110}$	903/792	2,2−2*g*	$-(77^{+\infty}_{-54})$†	RG0	Bodenstedt *et al.* (1960)
			$-(15.1^{+1.0}_{-0.8})$	RG0	Körner *et al.* (1964)
			$-(20^{+7}_{-5})$	RP0	Zupancic *et al.* (1969)
			$-(18.7^{+4.6}_{-3.1})$	RG1	Doubt *et al.* (1970)
			$-(19^{+11}_{-5})$	AD1	Milner *et al.* (1971)
			−16.65(85)	RD1	Butz *et al.* (1972)
			$-(22^{+6}_{-4})$	RG2	Canty *et al.* (1973)
			−18.2(1.2)	RD1	Hubel *et al.* (1973)
			−16.1(9)	RD1	Krane *et al.* (1973)
			−16.7(5)		
	1006/895	3,2−2*g*	$-(6^{+24}_{-3})$†	RG0	Bodenstedt *et al.* (1960)
			$\|\delta\| \geq 12$†	RG1	Doubt *et al.* (1970)
			$-(13.1^{+3.7}_{-2.1})$	RG2	Canty *et al.* (1973)
			−17.5(1.2)	RD1	Hubel *et al.* (1973)
			−13.2(9)	RD1	Krane *et al.* (1973)
			−14.7(1.0)	$r = 1.5$	
	1006/642	3,2−4*g*	$-(8.5^{+2.1}_{-1.4})$	RG2	Canty *et al.* (1973)
			−6.7(1.8)	RD1	Hubel *et al.* (1973)
			−8.5(7)	RD1	Krane *et al.* (1973)
			−8.3(6)		
	1135/771	4,2−4*g*	$\|\delta\| \geq 14$	RD1	Hubel *et al.* (1973)

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
			$-(6.3^{+3.2}_{-2.0})$	RD1	Krane *et al.* (1973)
			$-(11^{+17}_{-4})$	$r=2.0$	
	1122/1011	2″−2	$2.3^{+0.7}_{-0.5}$	RD1	Krane *et al.* (1973)
	1386/1275	2‴−2	6^{+6}_{-3}	RD1	Milner *et al.* (1971)
			$58^{+\infty}_{-40}$	RD1	Krane *et al.* (1973)
			$28^{+\infty}_{-17}$	$r=1.4$	
$^{186}_{74}W_{112}$	737/615	2′−2	$-(30^{+25}_{-10})$	RD0	McGowan and Stelson (1961a)
			Ad $-(11^{+4}_{-3})$	RD1	Milner *et al.* (1971)
	1286/1164	2″−2	13^{+70}_{-6}	RD1	Milner *et al.* (1971)
$^{186}_{76}Os_{110}$	767/630	2′−2	$-(150^{+\infty}_{-100})$	RG0	Bodenstedt *et al.* (1961)
			$\lvert\delta\rvert > 20$	RG0	Vervier (1963)
			$-(10^{+22}_{-4})$	RG2	Krane *et al.* (1971)
			$-(50^{+\infty}_{-30})$		
			$13.0^{+5.5}_{-3.0}$	RG0	Schotzig *et al.* (1969)
			$11(\infty)$	RD1	Spanhoff *et al.* (1978)
	910/773	3−2	$-(13^{+9}_{-6})$	RG2	Krane *et al.* (1971)
	1070/636	4′−4	11^{+45}_{-5}	RD1	Spanhoff *et al.* (1978)
$^{188}_{76}Os_{112}$	633/478	2′−2	$-(24^{+7}_{-4})$	RG0	Wiedling (1956)
			$\lvert\delta\rvert \geq 12$	RG0	Arns *et al.* (1960)
			$-(14^{+11}_{-4})$	RG0	Yamazaki (1963)
			$-(160^{+\infty}_{-130})$	AD1	Casten *et al.* (1969)
			$37^{+\infty}_{-20}$	AD1	Milner *et al.* (1971)
			$-(12.3^{+3.5}_{-2.2})$	RG2	Krane *et al.* (1971)
			Ad $-(23^{+9}_{-5})$	$r=1.58$	
	790/635	3−2	$-(8.3^{+12.0}_{-3.0})$	RG0	Yamazaki (1963)
			Ad $-(6.9^{+2.9}_{-1.6})$	RG2	Krane *et al.* (1971)
$^{190}_{76}Os_{114}$	557/371	2′−2	$-(14^{+11}_{-4})$	RG0	Yamazaki (1963)
			$-(11^{+7}_{-4})$	AD1	Casten *et al.* (1969)
			$-11(3)$	AP0	Robinson *et al.* (1969a)
			$-(6.5^{+1.7}_{-1.1})$	RP0	
			$-(8.5^{+1.0}_{-0.8})$	RG2	Krane *et al.* (1971)
			$-(8.6^{+2.8}_{-1.7})$	AD1	Milner *et al.* (1971)
			$-(11.4^{+4.6}_{-2.6})$	RG2	Helppi *et al.* (1974)
			$-(9^{+8}_{-3})$		
			$-(9.2^{+0.8}_{-0.7})$		
	755/569	3−2	$-(9.0^{+2.6}_{-1.6})$	RG2	Krane *et al.* (1971)
			$-(9.8^{+2.4}_{-1.7})$	RG2	Helppi *et al.* (1974)
			$-(9.4^{+1.8}_{-1.2})$		
			$14^{+\infty}_{-7}$	RP0	Yamazaki (1963)
	755/208	3−4	$-(17^{+11}_{-5})$	RG2	Helppi *et al.* (1974)
	755/198	3−2′	$-(6.4^{+2.4}_{-1.4})$		
	955/407	4′−4	$-(3.3^{+0.7}_{-0.5})$		
	1163/407	4″−3	$-(5^{+27}_{-3})$		
	1205/656	5−4	$-(9^{+7}_{-3})$		

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method		Reference
$^{192}_{76}Os_{116}$	489/283	2′−2	$-(5.2^{+1.6}_{-1.1})$	AD1	Casten *et al.* (1969)
			$-(4.7^{+0.7}_{-0.6})$	AP0	Robinson *et al.* (1969a)
			$-(3.0^{+0.9}_{-0.7})$	AD1	Milner *et al.* (1971)
			−3.8(7)	RG1	Becker *et al.* (1975)
			−4.2(4)		
	690/484	3−2	$-(10.9^{+2.1}_{-1.5})$	RG1	Grabowski (1969)
			$-(10^{+8}_{-3})$	RG1	Khan *et al.* (1969)
			$-(7.6^{+2.2}_{-1.4})$	RG1	Beraud *et al.* (1970)
			−5.8(8)	RD1	Hirschfeld and Hoppes (1970)
			$-(7.2^{+1.3}_{-1.0})$	RG2	Helppi *et al.* (1974)
			$-(10.2^{+1.1}_{-0.9})$	RG1	Becker *et al.* (1975)
			$-(9.2^{+0.9}_{-0.8})$	$r=1.6$	
	690/201	3−2′	$\lvert\delta\rvert \geq 1.9$	RD1	Hirshfeld and Hoppes (1970)
			$-(3.7^{+3.3}_{-1.5})$	RG2	Helppi *et al.* (1974)
			Ad $-(4.7^{+1.2}_{-0.9})$	RG1	Becker *et al.* (1975)
$^{188}_{78}Pt_{110}$	606/340	2′−2	$-(54^{+39}_{-17})$	AD1	Yoshikawa *et al.* (1972)
			$-(3.6^{+99}_{-3.1})$	AD1	Numao *et al.* (1977)
			$-(30^{+30}_{-15})$		
$^{190}_{78}Pt_{112}$	598/302	2′−2	$6.8^{+3.0}_{-1.2}$	AD1	
$^{192}_{78}Pt_{114}$	612/296	2′−2	$6.5^{+1.9}_{-1.3}$	RG0	Mraz (1957)
			$7.2^{+2.6}_{-1.6}$	RP0	Kukok *et al.* (1967)
			$6.5^{+1.2}_{-0.9}$	RG0	Koch *et al.* (1967)
			10(1)	RG1	Hamilton and Davis (1968)
			$9.1^{+2.7}_{-1.7}$	RG2	Grabowski (1969)
			$\lvert\delta\rvert \geq 4$	RG1	Khan *et al.* (1969)
			15^{+10}_{-5}	RD1	Reid *et al.* (1969)
			6^{+3}_{-1}	RD1	Hirshfeld and Hoppes (1970)
			8.8(5)	RG2	Holm (1973)
			8.8(3)	RG2	Helppi *et al.* (1974)
			6(2)	RG1	Katayama *et al.* (1975)
			10^{+3}_{-2}	RG0	Pande and Singh (1975)
			Ad 8.84(26)		
			5.4(2)	ELR	Voinova *et al.* (1974)
	921/604	3−2	$-(2.1^{+0.3}_{-0.2})$	RG1	Hamilton and Davis (1968)
			−2.0(2)	RG1	Grabowski (1969)
			−1.5(1)	RD1	Reid *et al.* (1969)
			−3(1)	RG1	Kenyon *et al.* (1969)
			−2.5(2)	RG1	Beraud *et al.* (1970)
			−1.5(1)	RD1	Hirshfeld and Hoppes (1970)
			$-(3.0^{+1.2}_{-0.9})$	RP0	Seubert and Silkinson (1970)
			$-3.3^{+0.7}_{-0.5}$	RP0	Hirose *et al.* (1970)
			−1.90(9)	RG2	Helppi *et al.* (1974)
			−2.5(2)	RG1	Katayama *et al.* (1975)
			−1.82(12)	$r=2.3$	
	921/308	3−2′	$\lvert\delta\rvert \geq 4$	RG0	Koch *et al.* (1967)
			$7.3^{+1.0}_{-0.8}$	RG1	Hamilton and Davis (1968)

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)		Method	Reference
			$9.9(1.0)$	RG2	Grabowski (1969)	
			$9.4(1.5)$	RG1	Kenyon *et al.* (1969)	
			$6.3^{+0.6}_{-0.5}$	RG1	Beraud *et al.* (1970)	
			$7.3(2)$	RD1	Reid *et al.* (1969)	
			$8(2)$	RG1	Khan *et al.* (1969)	
			$7.1(6)$	RD1	Hirshfeld and Hoppes (1970)	
			$11^{+\infty}_{-6}$	RP0	Hirose *et al.* (1970)	
			$4.4^{+1.3}_{-0.7}$	RG0	Singh and Dahiya (1972)	
			$9.1^{+\infty}_{-7.0}$	RG2	Holm (1973)	
			$8.1^{+1.4}_{-1.0}$	RG2	Helppi *et al.* (1974)	
			$7.4(4)$	RG1	Katayama *et al.* (1975)	
			Ad $7.3(3)$	$r=1.6$		
	1201/417	$4'-4$	$\lvert\delta\rvert > 8$	RG1	Khan *et al.* (1969)	
			$\lvert\delta\rvert > 11$	RG1	Kenyon *et al.* (1969)	
			$\lvert\delta\rvert > 1$	RD1	Reid *et al.* (1969)	
			$-(4^{+7}_{-3})$	RD1	Hirshfeld and Hoppes (1970)	
			$-(7^{+4}_{-3})$	RG2	Helppi *et al.* (1974)	
			Ad $-(20^{+\infty}_{-12})$			
$^{194}_{78}Pt_{116}$	622/294	$2'-2$	30^{+39}_{-11}	RG1	Hamilton (1969)	
			$14.3(2.1)$			
			$27(5)$	RG1	Katayama *et al.* (1975)	
			Ad 19^{+5}_{-3}			
	924/594	$3-2$	$\lvert\delta\rvert > 10$	RG1	Singh and Johns (1973a)	
	1513/1184	$2''-2$	$0.9(1)$			
	1623/1294	$2'''-2$	$-0.9(1)$			
$^{196}_{78}Pt_{118}$	688/333	$2'-2$	$-5.4(14)$	RG0	Steffen (1953)	
			$-5.0(5)$	RG0	Ikegami *et al.* (1963)	
			$-4.9(2)$	RP0	Pettersson *et al.* (1965b)	
			$-4.03(12)$	RG1	Hamilton (1969)	
			$-5.7(3)$	RG2	Krane *et al.* (1971a)	
			Ad $4.8(2)$	$r=3.0$		
$^{198}_{80}Hg_{118}$	1088/676	$2'-2$	$0.90^{+0.14}_{-0.09}$	RG0	Schrader (1953)	
			$1.1 \le \delta \le 2.0$	RG0	Schiff and Metzger (1953)	
			$0.7 \le \delta \le 1.8$	RG0	Jech *et al.* (1964)	
			$0.90^{+0.10}_{-0.08}$	RG0	Keszthelyi *et al.* (1964)	
			$0.95^{+0.12}_{-0.09}$	RG0	Pettersson *et al.* (1965a)	
			$1.2 \le \delta \le 2.0$	RG0	Uhl and Warhanek (1966)	
			$1.2 \le \delta \le 2.1$	RG0	Koch *et al.* (1967)	
			$1.05(8)$	RG1	Beraud *et al.* (1971)	
			$1.07^{+0.18}_{-0.10}$	RG1	Pakkanen (1971)	
			$0.96(6)$	RG0	Venkata Ramana Rao and Lakshminarayana (1972)	
			$1.16(3)$	RG0	Kawamura and Hisatake (1974)	
			$1.14(4)$	$r=1.5$		
	1419/1008	$3-2$	$1.3^{+0.3}_{-0.4}$	RG1	Beraud *et al.* (1971)	
			$1.3^{+0.3}_{-0.4}$	RG1	Pakkanen (1971)	
			$1.3(2)$			

TABLE I. *(Continued).*

Nucleus	Initial/Transition energy (keV)		δ(E2/M1)	Method	Reference
	1613/1201	2″−2	$-(0.29^{+0.05}_{-0.04})$	RG1	Beraud *et al.* (1971)
			−0.15(5)	RG1	Pakkanen (1971)
			$-(0.25^{+0.08}_{-0.06})$	$r=2.0$	
	1833/1421	2‴−2	Ad −0.17(3)	RG1	Beraud *et al.* (1971)
			$-(0.18^{+0.06}_{-0.05})$	RG1	Pakkanen (1971)
$^{206}_{82}Pb_{124}$	1341/538	3−2	−0.033(5)	RD1	Kaplan *et al* (1973)
			0.006(6)	AD1	Koyama *et al.* (1977)
			−0.22(8)	AD1	McConnell *et al.* (1977)
	1684/343	4−3	−0.027(3)		
$^{212}_{84}Po^{\dagger}_{128}$	1513/785	2′−2	$0.10^{+0.02}_{-0.03}$	RG0	Gangrskii *et al.* (1960)
			0.066(24)	RG0	Giannini *et al.* (1961)
			0.083(17)		
	1806/1079	2″−2	Ad −3(1)	RG0	Gangrskii *et al.* (1960)
			0.09(8)	RG0	Giannini *et al.* (1961)
$^{214}_{84}Po_{130}$	1378/769	2′−2	$4.3^{+4.5}_{-1.8}$	RG0	Taylor *et al.* (1961)
			$2.6^{+3.8}_{-1.9}$	RG1	Gupta and Sastry (1972)
			$3.7^{+2.5}_{-1.4}$		
	1544/935	3−2	$\lvert\delta\rvert \leq 0.4$	RG0	Bishop (1958)
	1730/1120	2″−2	0.05(5)		
	1848/1238	2‴−2	0.11(4)		
$^{232}_{90}Th_{142}$	774/724	2,0−2*g*	$-(1.5^{+2.8}_{-0.7})$	AD1	McGowan (1972)
	785/735	2,2−2*g*	23(10)		

^{48}Ti. Angular distribution measurements for additional transitions in ^{48}Tl have been published in Bardin *et al.* (1974). The δ values given there are derived from a statistical model analysis.

^{74}Zn 2′−2. A straight average was taken because the values do not overlap within their errors.

^{74}Se 2′−2. Since the individual results are highly conflicting, we have performed an unweighted average.

^{76}Se 2′−2. With NaI detectors it might be difficult to discriminate against close-lying γ transitions as indicated by highly incompatible A_ν coefficient in Kraushaar and Goldhaber (1953), Fischbeck and Newsome (1963), and Sathoff *et al.* (1963).

^{76}Se 2″−2. The results of the two earlier investigations with NaI detectors might be in error because of a close-lying 1213-keV transition. This is probably reflected in the discrepancy of 4 standard deviations between A_2 and A_4 as given by Sathoff *et al.* (1963) The value $\delta=-(0.42^{+0.08}_{-0.06})$ quoted by Krane for Nagahara (1973) is the lower solution from A_2, but this δ is not consistent with that from A_4, where $|\delta|=0.9(2)$. A consistent δ extracted from both A_2 and A_4 is given in this table for Nagahara (1973). While this latter δ still favors the −0.49 choice of Barclay and Perczuk (1976), it is not clear how to average the two results in our table, and so an average is not given.

^{82}Kr 2′−2. Since there is a discrepancy in the δ value extracted from the average A_2 and A_4 values, $\delta(\bar{A}_2)=2.6(2)$ and $\delta(\bar{A}_4)=2.0(3)$, we quote as adopted results the range including both.

^{82}Kr 3−2 and 3−2′. In view of the consistency of the data, other results for this transition in coincidence with other than the ground-state decay have been omitted, in part because they are less accurate, and in part because the multipolarity of the gating transition has not been determined independently.

^{102}Ru 2′−2. Older Na-I results are not given, since they could not resolve the 628−472 from the 631−472-keV cascade. This complexity undoubtedly is responsible for the inconsistent δ values from A_2 and A_4 in the omitted values and makes questionable the NaI results of Hisatake (1961), even though a consistent δ is obtained from A_2 and A_4 there. Even with Ge(Li) detectors, the decay scheme apparently is too complex to obtain a meaningful result, as indicated by the inconsistent δ values from the two most recent investigations.

^{106}Pd 3−2. The angular correlation and linear polarization measurements with NaI detectors given in Weight *et al.* (1968) have been neglected because of the inconsistency of the δ's from A_2 and A_4 in the former (to obtain a consistent δ would require chang-

TABLE I. *(Continued).*

ing the error limits on A_2 and A_4 at least 6 standard deviations) and the incompatibility of the δ from the two experiments. In Schoeters *et al.* (1975) internal conversion data were used to rule out a higher solution for δ which then was omitted from their paper. The conversion coefficient argument, however, is weak. Their higher value is from Krane (1980). Finally, note that the independent measurements of Tivin *et al.* (1977) are not consistent within their quoted errors.

^{108}Pd $2''-2$. The NaI result $\delta=0.24(4)$ of Okano *et al.* (1971) has been omitted, since it could have included annihilation summing. Such summing also may be supported by the slight discrepancy between δ from A_2 and A_4.

^{110}Cd $3-2$. There is a marked difference in the averaged δ values as determined by the angular correlation of the $5-3-2$ cascade $-0.28(2)$ (Funk and Wiedenbeck, 1958; Knipper, 1958; Cappeller and Ganssauge, 1959; Taylor and Frisken, 1959; Munnich *et al.*, 1964; Krane and Steffen, 1970; Sud *et al.*, 1970; and Gardulski and Wiedenbeck, 1973) and that of the $3-2-0$ cascade investigated primarily by the same authors $-0.48(2)$. The latter value is more in agreement with those obtained by other methods, and the former were neglected. However, the remaining accurate data fall into two separate groups, and averages for both groups are given.

^{110}Cd $3-2'$. The result of Gardulski and Wiedenbeck (1973) is not consistent in A_ν even within 3 standard deviations.

^{112}Cd $2'-2$. The third result $\delta=4.0(7)$ from Wallace *et al.* (1972) was not corrected for the contribution of the 693-keV transition.

^{116}Sn $2'-2$. Earlier results with NaI detectors from Scharenberg *et al.* (1956) and Bolotin (1964) have been excluded because competing cascades were present or A_4 was not quoted.

^{132}Xe $3-2$. In view of the difference in δ from A_2 and A_4, 0.30(4) and ≥ 0.5, respectively, of Robinson *et al.* (1962), we prefer the result of Krane and Steffen (1971c).

^{134}Xe $2'-2$. The solution $\delta=2.4(2)$ of Gualda *et al.* (1974) from A_2 would require a 3σ increase in A_4 and this seems improbable. Therefore we quote the value 0.04(6) which is consistent with A_2 and A_4.

^{134}Ba $2'-2$. A close-lying transition of 569 keV is probably responsible for the inconsistent A_2 and A_4 result of Munnich *et al.* (1963), which was thus excluded, and for the differences between the NaI- and NaI-Ge(Li) results and the more recent data obtained with two Ge(Li) detectors. However, the most recent work with two Ge(Li) detectors has the opposite sign. We adopted the negative value because of the agreement of two groups, but this is not a strong argument.

^{134}Ba $3-2$. The reported δ values for this weak transition vary over a considerable range even for those results which are consistent for A_2 and A_4 (inconsistent values from A_2 and A_4 were excluded). The two most recent values do not agree. One can say only that δ is in the range of 0.3 and 1.8.

^{140}Ce $3-4$. A total of 17 values have been reviewed for this transition. Four older references give only A_2 coefficients. About half of the remaining data are inconsistent in A_ν, generally so much so that an error increase did not seem appropriate.

^{140}Ce $4'-4$. *Note in proof.* D. Hamilton (1981) pointed out that the δ value for this transition by Wiedenbeck and Raeside (1971) was not correctly extracted by Krane (1977). Hamilton's analysis yielded $\delta=-0.36$. This new value is not included in the average because it was not extracted from the original data in a manner consistent with the other data.

^{140}Ce $2''-2$. The interference of 918-keV line could not be resolved in the NaI work of Cords (1969), Bès (1963), or Simons *et al.* (1963).

^{142}Ce $2'-2$. The result of Basinger *et al.* (1975a) is inconsistent in A_ν. The authors give $|\delta|=0.61(18)$ from A_4, while Krane in his review quotes $\delta=-(0.28^{+0.10}_{-0.07})$ from A_2 as the recommended value for this transition. If the errors are increased by a factor of 2 on A_ν, one derives from A_2 the value given in the table. In view of this discrepancy, we have not evaluated other cascades which have been measured with the $2'-2$ as intermediate transition.

^{114}Nd $2'-2$. Behar *et al.* (1974) present arguments that earlier results might be in error because of a close-lying doublet.

^{150}Sm. In Reddingius and Postma (1969) only anisotropies of angular distribution measurements are given. The percentage M1 admixtures are in agreement with the δ values listed in the table.

^{152}Sm Barclay and Perczuk (1975). The value $\delta=-5.7(2.1)$ is quite different from $\delta=-(9^{+\infty}_{-6})$ as calculated from the angular distribution coefficients.

^{152}Sm, ^{154}Gd $3,2-2g$. While general agreement is found among most investigations concerning ^{152}Sm and ^{154}Gd, these are two different groups of results, however, for the $3,2-2g$ transitions. Here the range of δ is such that A_2 is large compared to the other angular correlations. Since a large A_2 is very sensitive to attenuations from hyperfine interactions, we have adopted the data of Rud and Nielsen (1970) and Lange *et al.* (1971), who measured this effect time differentially for the particular sources used to determine the mixing ratios. For ^{152}Sm, the difference of the result of Kalfas *et al.* (1973) to the adopted value can be reduced by a factor of 2 if $G_2\sim 0.95$ is applied instead of neglecting any attenuation in the liquid source. In the case of ^{154}Gd the δ values of the above-mentioned references are confirmed by two other measurements, one of which is via a cascade not involving the long-lived 2^+ state.

^{152}Gd $3,2-2g$. The two groups of results are distinguished by their A_4 coefficients. Since the 1434-keV state might belong to the γ band, we have adopted the higher solution of δ. The result of Debrunner and Kündig (1960) is inconsistent in A_ν.

^{154}Gd. For the $6_\beta-6g$, $8_\beta-8g$, and $10_\beta-10g$ transitions, Gono and Sugihara (1974) extracted the δ values from the A_2/A coefficients of Ward *et al.* (1973) where the theoretical A_4 coefficients were assumed for the stretched E2 transitions. Nevertheless, these results are believed to provide some of the most accurate values for high-spin states in beta bands.

^{154}Gd $4,0-4g$. At this range of δ, the A_2 of $4-4-2$ cascade is flat and the normally separated solutions merge.

^{156}Gd $2,2-2g$. Older works, Cline and Heath (1961) and Bauer and Deutsch (1962), with only NaI detectors have been excluded because of the complexity of the decay scheme.

^{156}Gd. The values quoted for Uluer *et al.* (1975) are based on those A_2 coefficients which were fitted simultaneously with A_4 and not for a calculated A_4.

^{160}Dy $2,2-2g$. The $299-879$-keV cascades have been analyzed with an averaged $\delta(299)=-0.16(6)$.

TABLE I. *(Continued).*

^{160}Dy 3,2−2*g*. The investigations of Johnson *et al.* (1960), Michaelis (1963), Gupta and Saha (1965), Reich and Cline (1965), and Jaklevic *et al.* (1967) might be affected by the poorer NaI resolution and/or the lack of accurate hyperfine attenuation factors, as seen in the discrepancy with more recent data. The result given by Krane for Fox *et al.* (1974) seems to be corrected for the strong 966-keV contribution not accounted for in this reference [see also comment ^{160}Dy, Fox *et al.* (1974).
^{160}Dy. Fox *et al.* (1974). The accuracy of the published values is questioned by the statement of the authors that assumptions were necessary in deriving the orientation coefficients.
^{162}Er 6,2−6*g*. Since there is an obvious misprint in Table 1 of West *et al.* (1976), the lower limit of the second solution for δ was estimated from Fig. 7.
^{166}Er, Bozek *et al.* (1961). The estimate $|\delta| \geq 10$ was obtained from a measurement of the anisotropy at 90° and 180°.
^{166}Er, Domingos *et al.* (1972). While the authors have performed a χ^2 analysis, the δ values are here derived from the experimental A_ν coefficients. In the case of 4,2−4*g* transition the method of accounting for the $m>0$ substate population by normalizing to the 2,2−0*g* angular correlation might be questionable because of the different order of Coulomb excitations to the two states. This seems to be reflected in the small overlap of the A_ν coefficients with the theoretically allowed range which here has been accounted for by an increase of the errors.
^{166}Er 5,2−4*g*. The result of Carlsson *et al.* (1972) has been corrected for competing cascades by Krane; nevertheless, A_4 is still about 6 standard deviations off the range of δ determined by A_2.
^{166}Er West *et al.* (1976). Considering the statistics of their published spectra and the sometimes widely fluctuating results of the mixing ratio within a given nucleus − e.g., ^{162}Er 5,2−6*g*—the angular correlation data seem to be more reliable in view of their consistency.
^{166}Er 8,2−8*g*, 9,2−8*g*, West *et al.* (1976). Their published results for these two transitions can be reevaluated by using the given angular distribution coefficients of the mixed and corresponding pure transitions. The results then are found not to be consistent in A_2 and A_4.
^{172}Yb 2,2−2*g*. Since the two results are highly conflicting, the value quoted is that of an unweighted average. It is improbable that a 5% impurity mentioned in Krane *et al.* (1976) can be responsible for this deviation.
^{178}Hf 2,0−2*g*, Because of the inconsistency of the experimental data the errors had to be increased. The δ values were obtained from A_4, the signs from A_2.
^{184}W, Bodenstedt *et al*, (1960); Doubt *et al.* (1970). The results of these publications have been corrected under the assumption of a pure electric hyperfine interaction.
^{212}Po. In reference Gangrskii *et al.* (1960) no A_ν coefficients are given. In Giannini *et al.* (1961) the 2′−2−0 cascade was fitted under the assumption $A_4=0$ based on conversion coefficients. For the 2″−2 transition we have adopted the higher solution of Grangrskii *et al.* (1960) since it is in agreement with the conversion coefficient of Giannini *et al.* (1961).

angular distribution measurements, which in subgroup R denotes nuclear orientation. The third label indicates the number of Ge(Li) detectors used. For example RG1 means a γ-$\gamma(\theta)$ with a NaI-Ge(Li) system. AD0 means in-beam $\gamma(\theta)$ with a NaI-detector. Electron measurements are indicated by an E and the technique—for example, LR—is L subshell ratios.

A star (*) at a particular δ value indicates that the errors of the angular correlation coefficients had to be increased (see below). The weighted average for the mixing ratio of a given transition is listed below the groups of individual data, when applicable, together with r, the ratio of external and internal errors (see below). In these cases the error limit for the average represents always the external error. Values excluded from the averaging procedure are listed below the average.

When two distinct groups of data appear they were averaged separately. The adopted value is denoted by Ad. This label also depicts that δ value which we judge to be the most likely one in cases where no average could be performed or none was necessary.

Comments on a particular transition, a specific reference, and adopted or averaged value are indicated by a dagger (†) and listed according to the nucleus and the transition or reference at the end.

2. Analysis of data

It is customary in determining the mixing ratio δ from measurements in radioactive decays and to a small extent also from in-beam work, to calculate first the expansion coefficients A_ν and extract δ from these values. Two of the in general four possible solutions from A_2 and A_4 have to overlap, and this procedure therefore can give a check on the validity of the corrections made—for admixtures from interfering cascades, attenuations of the angular correlation, etc.

Especially in midrange of the mixing ratio where the accuracy in determing δ from A_2 and A_4 becomes comparable, it might be more appropriate to directly fit δ to the experimental count rates. The problems arising thereby are the error assignments in a nonlinear fit [see Rogers (1975)] in addition to the fact that these count rates might not be totally independent because of normalizations and other corrections. Since only the expansion coefficients are given in the literature, however, one has to rely on these. The reported errors of A_ν are assumed to correspond to 1 standard deviation, i.e., a 68% confidence level. The A_ν coefficients, however, are not independent data, but rather are correlated. This fact seems to be neglected by some authors; if the A_4 is not

consistent with either value of δ extracted from A_2, they just quote one of these for a variety of different reasons. Thereby it is neglected that if A_4 would be fixed to the correct value, A_2 would change too. Some authors even do not trust their measured A_4, even though it is consistent with one solution for δ; they take the other solution based on nuclear systematics.

Even though the A_ν are not independent, we adopt here the standpoint that they have to overlap in their ranges for the same δ at least to about 68%. In general, when values from A_2 and A_4 did not overlap, the errors were increased rather than to discard this result, since the measurements for a given isotope are so few. This was done for results which do not deviate more than $2-3$ standard deviations unless several accurate measurements were already available. Results with larger deviations have not been listed. The errors were also increased in situations where the experimental A_ν's only barely intersect the theoretically possible ranges.

In general, when more than one measurement of a particular δ is reported in one reference, only the averaged or most accurate value is given. In conflicting situations, we give all the individual results. Also, when there are few data on a transition, references which give only the order of δ without errors are included; otherwise, these are normally omitted. When a measurement cannot distinguish between the two solutions of the mixing ratio, we quote for it only that value which is in agreement with other works; otherwise, both are given.

In most cases where δ is very large or small, δ is more accurately determined by A_2, which has larger sensitivity, than by A_4. In the midrange, however, the situation may occur that from A_2 only the sign of δ can be inferred. The δ values listed in the table may deviate slightly from those given in the references, since we recalculated δ from the stated A_ν's. Differences can arise from rounding off the results especially when δ was determined by interpolation out of tables. Since the dependence of δ on A_ν is not linear, we give asymmetric errors unless the difference is marginal. Ranges are quoted in cases where the two solutions merge.

When looking at the total set of data on a particular transition and finding them largely conflicting, we are faced with the problem of judging them. In these cases we have tried to choose for the averaging procedure the values which seemed to be reliable on the basis of several considerations, such as how much was known about the decay scheme, which detectors were used, number of angles at which the experiment was performed, and knowledge of hyperfine attenuations. In these cases an unavoidable personal bias may be introduced and in these instances we give a comment to state our arguments for that particular choice.

The situation can become quite complex when the same authors present conflicting results, as, for example, for the $3-2$ transition of 1505 keV in ^{110}Cd. Here the averaged results of the $5-3-2$ and $3-2-0$ cascades differ by 10 standard deviations. Unfortunately, comments about such discrepancies are seldom, if ever, given by the original authors. In one case for ^{110}Cd, even though one of the results is inconsistent in A_2 and A_4, the data of both cascades were averaged. In addition, too small an error was quoted there on the mean, since both values are not compatible within their assigned errors. This is just one example showing that the errors of individual results in some cases are unrealistically small, presumably from the neglect of some systematic error. Here we wish to emphasize that when only one or two measurements exist for a transition, one may want to assess how much care was given to eliminating systematic errors from the results.

As noted in the earlier review by Hamilton (1971), when there are several measurements of one δ, some values must deviate from each other by more than one standard deviation if the errors are statistical (since 1σ represents only a 68% probability). Unfortunately, the spread in the values sometimes reaches up to 5σ in data where errors of a few percent are reported. It also was pointed out by Hamilton (1971) that in cases where A_2 is between -0.06 and -0.12 in a $2^+-2^+-0^+$ cascade that very high statistical accuracy is needed even to distinguish the sign of δ. In such a case, 1 standard deviation in the error limits may include only one sign for δ, but two σ limits may include both signs to make a definitive interpretation questionable. Similar ambiguities occur in Coulomb excitation angular distribution work when δ is large. There, too, one cannot uniquely establish the sign of δ. If the error limits on δ extend to infinity, one cannot establish the sign of δ. One must also remember that 2σ limits on δ must be obtained from 2σ limits on A_ν because of this nonlinear variation with δ and not from a doubling of the 1σ limits on δ.

When several results are available, the following averaging procedures were used. The averaging of a set of n reliable data $A^i \pm \Delta A^i$ was performed as an error weighted mean for A_2 and A_4

$$A = \sum_{i=1}^{n} \frac{A^i}{(\Delta A^i)^2} \Big/ \sum_{i=1}^{n} (\Delta A^i)^{-2} ,$$

with the standard deviation (internal error) of the mean given by

$$\Delta A = \left[\sum_{i=1}^{n} (\Delta A^i)^{-2} \right]^{-1/2} .$$

The normalized residuals

$$r^i = (A^i - A)/\Delta A^i ,$$

were computed to give an estimate on the compatibility of each value with the total set of data, since the contribution of $(r^i)^2$ to Q^2 is expected to be about unity. For normal distributed A^i,

$$Q^2 = \sum_{i=1}^{n} (r^i)^2$$

is χ^2 distributed with the expectation value of $n-1$. Because the number of experiments on a particular transition is usually small, we rejected a result only if its r^i

was much larger than 2, keeping values with large residuals in a Q^2, which may exceed its expectation value of $n-1$. Here we quote the external error of the average $\Delta A \cdot r$, where

$$r=[Q^2/(n-1)]^{1/2} .$$

This is equivalent to increasing all the individual errors by this factor to get, if recalculated, $Q^2=n-1$. This procedure might be unfair to a particularly accurate result, but the data are normally too scarce to subject them to a rigorous statistical test. On the other hand, there are times when the reported error limits of a particular result appear much too small. So there is some balancing in this procedure. The above averaging procedure follows the one given in Cohen and DuMond (1965) and Taylor *et al.* (1969).

In cases where two distinct sets of data occur, the adopted average is identified by an Ad. There exist a few transitions where a weighted average of δ would have a vanishingly small probability of representing the true value. Here we quote a straight average. In some cases, it may not be possible to determine a definite value or even the sign of δ. The experimental values, consistent in A_2 and A_4, rejected by the two above given judgments are listed below the average.

In experiments with angular distribution or correlation following a nuclear reaction, the situation is complex in that one has in general to fit the population parameters, too, or estimate the attenuation with respect to the case of maximum alignment. The experimental coefficients A_ν depend strongly on the reaction mechanism and can therefore not be compared for different experiments. In a major part of investigations of γ rays in nuclear reactions, the mixing ratio δ is directly fitted to the experimental count rates. Unfortunately, the method of error analysis is not always stated and seems not to be standard yet [see Rogers (1975)]. Where possible, we have extracted the appropriate A_ν^γ coefficients from the experiment, when radioactivity and in-beam measurements were to be averaged. In other cases we have had to rely on the quotation of the specific reference and to average the δ values directly. To account for asymmetric errors, we have calculated A_2 from δ and averaged these.

In addition to not explaining the method of errors analysis, the sign convention for δ is not always given. Since the experimental methods mostly refer to Litherland and Ferguson (1961), the definition of the reduced mixing elements is equivalent to that of Rose and Brink (1967), which is just opposite in sign to the convention of Krane and Steffen (1970). In cases where doubt exists, we have assumed the former convention was used. To avoid such confusion of error analysis and sign, it would be desirable for future publications to give the corresponding A_ν^γ coefficients.

B. Procedures and results for E0/E2 mixing ratios in $\Delta I = 0$ transitions

Experimental data on E0/E2 mixing ratios are presented in Table II. Values of q^2(E0/E2) for K-shell electrons were extracted from experimental conversion coefficients, α_K, which equal the intensities of the $E0_K+E2_K+M1_K$ electrons divided by the E2 + M1 γ-ray intensities per the same unit of time. Only when the E2/M1 admixture is known can a definite value for an E0/E2 admixture be extracted. Thus cases where the E2/M1 mixing ratio is not known are excluded from this survey. Also excluded in Table II are transitions from 0^+ states where one can compare the E0 strength in a $0^+\rightarrow 0^+$ transition with the E2 strength in a $0^+\rightarrow 2^+$ transition from the state. However, ρ(E0) for $0^+\rightarrow 0^+$ transitions are included later in Table IX.

In Table II, the second column gives the energy of the level being depopulated in the nucleus shown in column 1. The energy of the $\Delta J=0$ transition from this level is shown in column 3 and the spins in column 4. Also noted in column 4 is the beta or gamma vibrational character of the initial level, if known. The final states are always in the ground band. Average values of the experimental K conversion coefficients are in a column 5 with theoretical E2 and M1 K conversion coefficients (Hager and Seltzer, 1968) in columns 6 and 7. In column 8 are δ(E2/M1) values from Table I. Then come the q values when measured directly as discussed below, the q^2 values, and the dimensionless ratios $X=\varepsilon^2\sim q^2(\text{E0/E2})\sim\rho^2(\text{E0})/B(\text{E2})$. In the calculations, $X=2.54\times10^9\times A^{4/3}\times E(\text{MeV})^5 q^2\alpha(\text{E2})/\Omega$ was used, where Ω and α were taken from Hager and Seltzer (1968, 1969).

In extracting q^2 from experimental conversion coefficients where

$$\alpha_{\text{expt}}=\frac{1}{1+\delta^{-2}}\{(1+q^2)\alpha(\text{E2})+\delta^{-2}\alpha(\text{M1},\lambda)\} , \tag{4.1}$$

and δ is the E2/M1 mixing ratio, one has the additional problem that there can occur changes in the conversion coefficients from the normal values from the penetration of the electrons into the nuclear volume (Church and Weneser, 1960; Hager and Seltzer, 1968). These penetration effects manifest themselves in additional contributions to the internal conversion but not to the γ-ray emission to thus increase the conversion coefficient. These effects are particularly important when the γ-ray emission is highly hindered (Listengarten, 1978). Penetration effects have not been observed in E2 transitions, which are often highly enhanced [see the reviews of Gerholm and Holmberg (1971) and Listengarten (1978)]. Penetration effects are reported in M1 transitions with the largest known effect ($\lambda=210\pm30$) for the 3×10^6 hindered transition in ^{181}Ta. These penetration effects are measured by the parameter λ, which is related to the ratio of the penetration matrix and gamma−ray matrix elements. Thus in Eq. (4.1) the M1 conversion coefficient is shown to depend on λ. In the notation of Hager and Seltzer (1968), this yields an M1 conversion coefficient given by

$$\alpha(\text{M1})[1+B_1(\text{M1})\lambda+B_2(\text{M1})\lambda^2] ,$$

where the B_1, B_2 are small expansion terms. For the ex-

TABLE II. Experimental data on q(E0/E2), q^2, and X(E0/E2) mixing ratios.

Isotope	Level (keV)	E_γ (keV)	$I_i - I_f$	$\alpha_K \times 10^{-3}$ expt.	$\alpha_K \times 10^{-3}$ E2*	$\alpha_K \times 10^{-3}$ M1*	δ** E2/M1	q E0/E2	$q^{2\dagger}$ E0/E2	X*** E0/E2	α_K, q Ref.‡
^{114}Cd	1209	651	2-2	2.73(30)	2.79	3.12	$-(1.22^{+0.55}_{-0.25})$		$-0.12(^{19}_{27})^{\dagger}$	$-0.02(3)^{\dagger}$	Smither (1961)
											Bäcklin *et al.* (1966)
	1364	806	2-2	3.33(40)	1.64	1.91	$0.09^{+0.08}_{-0.05}$		108^{+192}_{-86}	$26(^{47}_{21})$	
^{144}Nd	1561	864	2-2	4.8(9)	2.64	4.1	$-1.6(5)$		0.9(5)	0.10(5)	Berzin *et al.* (1970)
^{150}Sm	1046	712	2-2	7.7(5)	4.46	7.79	$-(4.8^{+0.5}_{-0.4})$		0.73(12)	0.050(8)	Baglin (1976)
	1449	676	4-4	14.7(1)	5.04	8.87	$-1.3(3)$		2.6(4)	0.17(3)	
^{152}Gd	931	586	2_β-2	20.7(23)	7.65	14.7	$-3.0(3)$		1.79(4)	0.070(2)	Gono *et al.* (1970),
											Zolnowski *et al.* (1971)
	1109	765	2_γ-2	5.50(159)	4.13	7.59	$4.3^{+0.7}_{-0.6}$		$0.30^{+0.41}_{-0.30}$	0.02(2)	Malmsten *et al.* (1967)
											Zolnowski *et al.* (1971)
											Baker *et al.* (1972)
^{152}Sm	810	688	2_β-2	34(1)	4.83	8.42	19^{+5}_{-4}		6.05(21)	0.41(1) Ad	Baglin (1980)
								2.5(3)	6.25(150)	0.43(10)	Stefánsson *et al.* (1972)
	1023	656	4_β-4	47(4)	5.42	9.47	2.1(3)		9.2(10)	0.58(6)	Baglin (1980)
	1086	964	2_γ-2	2.38(13)	2.28	3.73	$-9.6(3)$		$0.04^{+0.06}_{-0.04}$	$0.005(^{7}_{5})$	Malmsten *et al.* (1967)
											Baker *et al.* (1972)
	1372	1005	4_γ-4	2.78(32)	2.09	3.38	$-(3.1^{+0.3}_{-0.2})$		0.30(18)	0.04(2)	
^{154}Gd	816	692	2_β-2	38.8(11)	5.18	9.71	$8.3^{+1.5}_{-1.1}$		6.6(2)	0.35(1)	Rud *et al.* (1971)
	1048	677	4_β-4	40.6(40)	5.44	10.2	3.0(13)		7.1(10)	0.36(5)	Rud *et al.* (1971), Gono and Sugihara (1974)
	1366	648	6_β-6	39(7)	6.03	11.4	$1.8^{+0.3}_{-0.2}$		6.9(19)	0.33(8)	Gono and Sugihara (1974)
	1756	612	8_β-8	53(7)	6.90	13.2	$1.2^{+0.4}_{-0.3}$		10.7(19)	0.46(8)	
	2194	557	10_β-10	46(12)	8.67	16.7	$1.1^{+0.5}_{-0.3}$		7.1(36)	0.26(13)	
	996	873	2_γ-2	3.46(9)	3.09	5.51	$-9.7(5)$		0.11(3)	0.009(2)	Rud *et al.* (1971)
^{156}Gd	1129	1040	2_β-2	12.4(8)	2.14	3.62	$-(14^{+\infty}_{-7})$		4.8(4)	0.56(6)	Hamilton *et al.* (1972)
	1298	1009	4_β-4	15.6(40)	2.27	3.89	no $\delta^{\dagger\dagger}$		6.4(20)	0.71(21)	
	1154	1065	2_γ-2	2.18(10)	2.04	3.42	$-(17.5^{+1.6}_{-1.4})$		0.07(5)	0.008(6)	
^{160}Dy	966	879	2_γ-2	3.36(10)	3.36	6.31	$-14.8(11)$		$0.00^{+0.030}_{-0.00}$	$0.0000(^{22}_{0})$	Tuli (1974)
								$-0.03(6)$	$0.0009(^{72}_{9})$	$0.00006(^{20}_{6})$ Ad	Zupancic *et al.* (1972)
											Zawislak *et al.* (1973)
^{178}Hf	1276	1183	2_0-2	12.7(5)	2.44	4.77	0.41(4)		23.5(40)	1.98(34)	Gizon *et al.* (1972)
											Hamilton *et al.* (1974)
	1496	1403	2_β-2	7.47(30)	1.77	3.16	$-0.75^{+0.19}_{-0.17}$		$7.5(^{+2.2}_{-1.9})$	0.90(27)	
^{182}W	1257	1157	2_β-2	6.6(6)	2.80	5.84	$-(8.7^{+5.5}_{-2.5})$		1.36(22)	0.097(16)	Westerberg *et al.* (1975)
								$\pm 1.13(13)$	1.28(29)	0.090(19)	
										0.094(12) Ad	

TABLE II. *(Continued.)*

Isotope	Level (keV)	E_γ (keV)		$\alpha_K \times 10^{-3}$ expt.	$\alpha_K \times 10^{-3}$ E2*	$\alpha_K \times 10^{-3}$ M1*	δ** E2/M1	q E0/E2	$q^{2\dagger}$ E0/E2	X*** E0/E2	α_K, q Ref.
^{182}W	1221	1121	2_γ-2	3.09(6)	2.98	6.31	$16.7^{+4.1}_{-2.7}$		0.033(20)	0.0022(14)	Westerberg *et al.* (1975)
								±0.16(9)	$0.026^{+0.036}_{-0.021}$	$0.0017(^{24}_{14})$	
										0.0020(10) Ad	
	1442	1113	4_γ-4	3.59(13)	3.02	6.42	$-(20^{+\infty}_{13})$		0.19(5)	0.012(4)	
								±0.41(9)	0.17(7)	0.011(4)	
										0.012(2) Ad	
^{184}W	903	792	2′-2	6.4(3)	5.91	14.9	−16.7(5)		0.08(5)	0.0026(17)	Doubt *et al.* (1970)
								0.18(19)	$0.032^{+0.10}_{-0.03}$	$0.0009(^{27}_{9})$	Samuelson *et al.* (1969)
								$0.30(^{+0.08}_{-0.03})$	$0.09^{+0.05}_{-0.02}$	$0.0029(^{16}_{6})$	Doubt *et al.* (1970)
								or $-(0.16^{+0.40}_{-0.12})$	$0.026^{+0.28}_{-0.24}$	$0.0008(^{70}_{7})$	Doubt *et al.* (1970)
										$0.0020(^{12}_{8})$ Ad	
^{188}Os	633	478	2′-2	23(3)	19.1	64.0	$-(23^{+9}_{-5})$		0.20(16)	0.0044(35)	Yamazaki (1963)
^{190}Os	557	371	2′-2	36(2)	34.9	124	$-(9.2^{+0.7}_{-0.8})$		$0.002^{+0.060}_{-0.002}$	$0.00002(^{80}_{2})$	Samuelson *et al.* (1969)
								−0.08(17)	$0.006^{+0.060}_{-0.006}$	$0.00001(^{40}_{1})$ Ad	
^{192}Pt	612	296	2′-2	67(1)	63.7	271	8.8(5)		$0.010^{+0.017}_{-0.010}$	$0.00003(^{5}_{3})$ Ad	Schmorak (1973)
								−0.10 to +0.15	≤0.022	≤0.00007	†††
^{194}Pt	622	293	2′-2	67(2)	64.0	277	19^{+5}_{-3}		0.038(35)	$0.00011(^{10}_{7})$	Bergman (1964), Bashandy (1971)
								−0.25(13)	$0.063^{+0.081}_{-0.049}$	$0.00017(^{23}_{13})$	Alwyn and Butt (1967)
										0.00014(5) Ad	
^{196}Pt	688	333	2′-2	56(3)	47.7	198	4.8(2)		$0.045^{+0.067}_{-0.045}$	$0.00017(^{26}_{17})$	Gerholm *et al.* (1962)
								−0.22(7)	$0.048^{+0.036}_{-0.021}$	$0.00018(^{14}_{10})$	Pettersson *et al.* (1965b)
								or 0.39(6)	0.15(4)	$0.00056(^{16}_{14})$	
								$-(0.23^{+16}_{-20})$	$0.053^{+0.100}_{-0.052}$	$0.00020(^{36}_{20})$	Doubt *et al.* (1971)
								or $0.44^{+0.09}_{-0.10}$	0.19(8)	$0.00071(^{26}_{30})$	
										$0.0036(^{10}_{8})$ Ad	
^{198}Hg	1087	676	2′-2	22.4(19)	10.4	35.5	1.14(4)		$0.18^{+0.33}_{-0.18}$	$0.0024(^{44}_{24})$	Elliott *et al.* (1954)
								−(1.1−1.6)	1.2−2.6	0.016−0.034	Sakai *et al.* (1964)
								or (0.8−1.6)	0.6−2.6	0.008−0.034	
										0.010(5) Ad	

TABLE II. (*Continued.*)

*The theoretical α_K values are from Hager and Seltzer (1968).
**The E2/M1 mixing ratios are from Table I.
***When one reference gives two q values with different signs, both the q^2 values were used in obtaining an adopted average for X.
†A minus sign has no significance except to show that the experimental α_K is less than the pure E2 value, so the E0 admixture is very small if present. With the exception of ^{114}Cd the lower error limits on the q^2 values were taken as zero (no E0 admixture).
††Since δ is not measured, it was assumed to be 3.0 as found in ^{154}Gd for the analogous transition.
†††The range of q values given are our best estimates for an average of the six measurements as reported in Voinova *et al.* (1974).
‡When no reference is given, the previous reference applies.

perimentally observed λ values (typically $\lesssim 40$) and for $q^2 \gtrsim 2$ and $\delta \gtrsim 3$, one can simply neglect the terms in λ in Eq. (4.1) in extracting q^2 from α_{expt}. These conditions clearly exist for the decays of beta-type vibrational levels in rare-earth nuclei and so terms in λ are neglected in these cases in Table II.

When the E0 intensity becomes very small, $\alpha_{\text{expt}} \approx \alpha(\text{E2})_{\text{theor}}$, one cannot obtain a reliable q^2(E0/E2) value from α_{expt}. However, the directional correlations between K- and L-shell conversion electrons and succeeding gamma rays are still sensitive to both the sign and magnitude of q and λ, as reviewed earlier by Gerholm and Pettersson (1966) and Gerholm and Holmberg (1971). Even when the E0 intensity is quite small, E0−E2 interference can appreciably alter the electron-γ correlation. It is also true that one can study E0 transitions in γ-γ directional correlations when the second transition in a triple cascade is the one of interest and is skipped, a γ_1-γ_3 correlation (Anian *et al.*, 1970). There is no E0−E2 interference term here and this method can yield a definite, nonzero q^2 only if q^2 is large. Thus this technique has not been used much. We have excluded the few values obtained by this technique because they all have very large errors that overlap zero.

In the e_K-γ directional correlation studies, one must know δ and use other data—for example, α_K, electron intensities like K/L_{III}, $L_{\text{I}}/L_{\text{II}}$ ratios, and/or e_L-$\gamma(\theta)$ data—to obtain both q and λ values simultaneously. Such measurements have been carried out for the 2^+_β-2^+_g and 2^+_γ-2^+_g transitions in ^{152}Sm and ^{160}Dy, respectively, and for ^{182}W−^{198}Hg. The q values obtained from them are given in Table II. For completeness, the α_{expt} values are given in these cases, too. One can see the lack of sensitivity of α in general in these cases. For ^{152}Sm, one has q^2 obtained by both e-$\gamma(\theta)$ and α_K and these agree well, as seen in Table II. For ^{182}W−^{198}Hg the δ's used in the analysis of the e-$\gamma(\theta)$ data are often somewhat different from our adopted values, but within error limits—for example, in ^{196}Pt our $\delta = 4.8(2)$ while 4.9(2) was used, for ^{182}W, $\delta_{ad} = 16.7^{+4.1}_{-2.7}$ while $\delta = 21^{+7}_{-5}$ was used. Even such differences in large δ values do not appreciably alter the q value. Since a major error in q^2 is associated with the e-$\gamma(\theta)$ coefficients, as seen by the variations in the different values when more than one measurement exists for one nucleus, we have not recalculated the q values for ^{160}Dy and ^{182}W−^{198}Hg. Because of an error in the sign of the E2/M1 interference particle parameters used in the analysis to extract q and λ values from e-γ correlation studies prior to 1964, these results are excluded from the survey unless they were reanalyzed by the authors. In measuring q values one often has two regions of allowed values of q which fit the data. While the two q values allowed have different signs, their magnitudes generally are similar so that q^2 and X are determined. Also, some of the earlier q measurements have been included only as average limits when needed to confirm the magnitude of q and others omitted when subsequent analyses have indicated that only upper limits on q and not the sign had been established [see Doubt and

TABLE IIIa. Adopted E2/M1 mixing ratios of 2'-2 transitions.

Nucleus	Initial/Transition energy (keV)	δ(E2/M1)	Nucleus	Initial/Transition energy (keV)	δ(E2/M1)
$^{16}_{6}C_{10}$	3980/2210	−0.18(15)	$^{72}_{34}Se_{38}$	1317/455	4.6(1.5)
$^{18}_{8}O_{10}$	3921/1939	−0.12(4)	$^{74}_{34}Se_{40}$	1270/635	$-(3.6^{+2.0}_{-1.0})$
$^{18}_{10}Ne_{8}$	3616/1729	−0.06(6)	$^{76}_{34}Se_{42}$	1216/657	5.4(2)
$^{20}_{10}Ne_{10}$	7421/5787	$8.4^{+1.5}_{-1.0}$	$^{78}_{34}Se_{44}$	1309/695	$3.5^{+2.6}_{-1.2}$
$^{22}_{10}Ne_{12}$	4457/3182	0.083(12)	$^{80}_{34}Se_{46}$	1450/783	$-(5^{+6}_{-2})$
$^{24}_{10}Ne_{14}$	3867/1886	0.15(15)	$^{80}_{36}Kr_{44}$	1256/639	$16^{+\infty}_{-8}$
		or 2.1(6)	$^{82}_{36}Kr_{46}$	1475/698	$1.7 \leq \delta \leq 2.8$
$^{22}_{12}Mg_{10}$	4402/3155	0.8(7)	$^{84}_{36}Kr_{48}$	1893/1012	$-(36^{+\infty}_{-25})$
$^{24}_{12}Mg_{12}$	4239/2869	−23(9)	$^{86}_{38}Sr_{48}$	1854/777	0.30(2)
$^{26}_{12}Mg_{14}$	2939/1129	−0.12(2)	$^{88}_{38}Sr_{50}$	3219/1382	0.04(2)
$^{28}_{12}Mg_{16}$	4557/3084	−0.035(30)	$^{88}_{40}Zr_{48}$	1819/761	−0.10(13)
$^{26}_{14}Si_{12}$	2780/990	−0.21(10)	$^{92}_{40}Zr_{52}$	1847/913	0.016(12)
$^{30}_{14}Si_{16}$	3498/1263	0.17(4)	$^{94}_{40}Zr_{54}$	1671/752	−0.22(10)
$^{32}_{14}Si_{18}$	4234/2291	−0.84(44)	$^{92}_{42}Mo_{50}$	3091/1582	$0.69^{+0.54}_{-0.38}$
$^{32}_{16}S_{16}$	4282/2052	$\delta > 1$	$^{94}_{42}Mo_{52}$	1864/993	−2.0(3)
$^{34}_{16}S_{18}$	3300/1170	−0.148(14)	$^{96}_{42}Mo_{54}$	1498/720	0.43(3)
$^{36}_{16}S_{20}$	4570/1280	0.07(4)	$^{98}_{42}Mo_{56}$	1432/645	0.58(5)
$^{34}_{18}Ar_{16}$	3288/1197	0.12(5)	$^{96}_{44}Ru_{52}$	1931/1099	$-(4.2^{+2.2}_{-1.4})$
$^{36}_{18}Ar_{18}$	4441/2471	$\lvert\delta\rvert \geq 1.5$	$^{98}_{44}Ru_{54}$	1414/762	$13.4^{+3.9}_{-2.5}$
$^{40}_{18}Ar_{22}$	2524/1063	$-(0.41^{+0.13}_{-0.16})$	$^{100}_{44}Ru_{56}$	1366/826	3.8(4)
$^{40}_{20}Ca_{20}$	5249/1545	13^{+6}_{-3}	$^{102}_{44}Ru_{58}$	1103/628	$\lvert\delta\rvert \geq 3$
$^{42}_{20}Ca_{22}$	2423/899	−0.18(2)	$^{104}_{44}Ru_{60}$	893/535	$-(18^{+6}_{-4})$
$^{44}_{20}Ca_{24}$	2656/1499	−0.123(16)	$^{102}_{46}Pd_{56}$	1534/978	$10.4^{+12.1}_{-3.7}$
$^{44}_{22}Ti_{22}$	2531/1448	$-(7.5^{+8.0}_{-2.5})$	$^{104}_{46}Pd_{58}$	1342/786	$11(^{+10}_{-3})$
$^{46}_{22}Ti_{24}$	2962/2073	1.28(18)	$^{106}_{46}Pd_{60}$	1128/616	−8.9(5)
$^{48}_{22}Ti_{26}$	2421/1438	0.15(7)	$^{108}_{46}Pd_{62}$	931/497	−3.1(4)
$^{50}_{22}Ti_{28}$	4311/2755	0.26(17)	$^{110}_{46}Pd_{64}$	814/440	$-(4.6^{+1.9}_{-1.2})$
$^{52}_{22}Ti_{30}$	2259/1212	0.03(10)	$^{106}_{48}Cd_{58}$	1718/1085	−0.73(14)
$^{50}_{24}Cr_{26}$	2922/2136	$0.03^{+0.06}_{-0.04}$	$^{108}_{48}Cd_{60}$	1603/970	$-(1.5^{+1.5}_{-0.6})$
$^{52}_{24}Cr_{28}$	2966/1532	−6.25(1.50)	$^{110}_{48}Cd_{62}$	1476/818	−1.30(40)
$^{54}_{24}Cr_{30}$	2620/1785	$-(0.36^{+0.29}_{-0.14})$	$^{112}_{48}Cd_{64}$	1312/695	−0.80(5)
$^{56}_{24}Cr_{32}$	1832/825	−1.8(1.0)	$^{114}_{48}Cd_{66}$	1208/650	$-(1.22^{+0.37}_{-0.16})$
$^{54}_{26}Fe_{28}$	2959/1530	0.11(4)	$^{116}_{48}Cd_{68}$	1212/699	$-(1.5^{+0.9}_{-0.5})$
$^{56}_{26}Fe_{30}$	2658/1811	−0.179(11)	$^{112}_{50}Sn_{62}$	2154/895	$3.8^{+2.5}_{-1.0}$
$^{58}_{26}Fe_{32}$	1674/864	−0.56(3)	$^{116}_{50}Sn_{66}$	2112/819	−1.76(12)
$^{58}_{28}Ni_{30}$	2775/1321	−1.14(11)	$^{118}_{50}Sn_{68}$	2043/813	$-(7^{+6}_{-3})$
$^{60}_{28}Ni_{32}$	2159/827	0.82(15)	$^{120}_{50}Sn_{70}$	2096/925	−1.43(25)
$^{62}_{28}Ni_{34}$	2302/1129	3.2(1)	$^{122}_{50}Sn_{72}$	2153/1013	4^{+2}_{-1}
$^{62}_{30}Zn_{32}$	1805/851	$-(1.2^{+0.5}_{-0.4})$	$^{124}_{50}Sn_{74}$	2130/998	$3.0^{+1.2}_{-0.6}$
$^{64}_{30}Zn_{34}$	1799/807	−1.6(4)	$^{122}_{52}Te_{70}$	1257/693	−3.48(4)
$^{66}_{30}Zn_{36}$	1872/833	−2.0(2)	$^{124}_{52}Te_{72}$	1326/723	−3.55(7)
$^{68}_{30}Zn_{38}$	1883/806	−1.46(10)	$^{126}_{52}Te_{74}$	1421/754	$-(5.6^{+0.5}_{-0.4})$
$^{66}_{32}Ge_{34}$	1693/736	$-(3.3^{+2.6}_{-1.8})$	$^{124}_{54}Xe_{70}$	846/492	$6.8^{+4.0}_{-1.5}$
$^{68}_{32}Ge_{36}$	1778/762	−0.09(2)	$^{126}_{54}Xe_{72}$	880/491	$13.5^{+3.0}_{-2.0}$
$^{70}_{32}Ge_{38}$	1709/668	$-(5.0^{+4.0}_{-1.5})$	$^{128}_{54}Xe_{72}$	969/526	6.1(5)
$^{72}_{32}Ge_{40}$	1464/630	−10.3(1.3)	$^{132}_{54}Xe_{78}$	1298/630	$4.8^{+1.2}_{-0.9}$
$^{74}_{32}Ge_{42}$	1608/609	3.3(3)	$^{134}_{54}Xe_{80}$	1613/766	0.04(6)
$^{76}_{32}Ge_{44}$	1109/545	3.5(1.5)	$^{132}_{56}Ba_{76}$	1032/567	$9.6^{+7.6}_{-2.9}$

TABLE IIIa. *(Continued.)*

Nucleus	Initial/Transition energy (keV)	δ(E2/M1)
$^{134}_{56}Ba_{78}$	1168/563	$-(7.6^{+0.8}_{-0.6})$
$^{140}_{56}Ba_{84}$	1511/908	$-(1.10^{+0.14}_{-0.10})$
$^{140}_{58}Ce_{82}$	2348/752	0.34(2)
$^{142}_{58}Ce_{84}$	1536/895	−0.10(5)
$^{144}_{60}Nd_{84}$	1561/865	−1.6(5)
$^{146}_{60}Nd_{86}$	1471/1017	13^{+19}_{-8}
$^{150}_{64}Gd_{86}$	1431/793	2.0(7)

Hamilton (1971) and Voinova *et al.* (1974) for examples of such]. Indeed, attaining a definitive measurement of the sign of q is difficult and requires several different accurate measurements.

V. ANALYSIS OF EXPERIMENTAL DATA AND COMPARISON WITH THEORETICAL CALCULATIONS

A. Systematics of δ(E2/M1) for 2′-2 transitions

The averaged experimental E2/M1 mixing ratios of transitions proceeding between the two lowest 2^+ states (and in deformed nuclei for the 2_β-2_g and 2_γ-2_g transitions) in even-even nuclei are collected in Tables IIIa, b, c, and d and displayed in Fig. 1 vs $\log(\delta/E)^2$. For comparison the single-particle estimate [Eq. (3.2)] and the Davydov-Filippov estimate [Eq. (3.13)] are included.

The single-particle limit is reached at or near some shell closures, but it is noteworthy that the double closed-shell nucleus ^{40}Ca exhibits one of the largest values in the low-mass region. The δ values for neutron closed-shell nuclei are in general lower than those for the proton closed-shell nuclei. This effect might be related to the neutron excess which stabilizes the collectivity of the latter species. Below $A \sim 60$ the reduced E2/M1 transition probabilities scatter between the single-particle

TABLE IIIb. Adopted E2/M1 mixing ratios of 2_γ-2_g transitions.

Nucleus	Initial/Transition energy (keV)	δ(E2/M1)
$^{150}_{62}Sm_{90}$	1194/860	$3.4^{+0.8}_{-0.6}$
$^{152}_{62}Sm_{90}$	1087/965	−9.6(3)
$^{152}_{64}Gd_{88}$	1109/765	$4.3^{+0.7}_{-0.6}$
$^{154}_{64}Gd_{90}$	996/873	−9.7(5)
$^{156}_{64}Gd_{92}$	1154/1065	$-(17.5^{+1.6}_{-1.4})$
$^{158}_{64}Gd_{94}$	1188/1108	$-(23^{+\infty}_{-14})$
$^{160}_{66}Dy_{94}$	966/879	−14.8(11)
$^{162}_{66}Dy_{96}$	890/808	$\lvert\delta\rvert \geq 20$
$^{164}_{66}Dy_{98}$	762/689	$-(7^{+\infty}_{-4})$
$^{166}_{68}Er_{98}$	787/705	$-(16^{+13}_{-5})$
$^{168}_{68}Er_{100}$	822/742	$\lvert\delta\rvert \geq 87$
$^{170}_{68}Er_{102}$	933/853	$-(55^{+\infty}_{-34})$
$^{172}_{70}Yb_{102}$	1466/1387	$-(4.4^{+4.5}_{-1.9})$
$^{178}_{72}Hf_{106}$	1174/1081	$\lvert\delta\rvert \geq 11$
$^{180}_{72}Hf_{108}$	1200/1107	$9.6^{+22}_{-5.8}$
$^{232}_{90}Th_{142}$	785/735	23(10)

TABLE IIIc. Adopted E2/M1 mixing ratios of 2_β-2_g transitions.

Nucleus	Initial/Transition energy (keV)	δ(E2/M1)
$^{150}_{62}Sm_{88}$	1046/712	$-(4.8^{+0.5}_{-0.4})$
$^{152}_{62}Sm_{90}$	811/689	19^{+5}_{-4}
$^{152}_{64}Gd_{88}$	931/586	−3.0(3)
$^{154}_{64}Gd_{90}$	816/692	$8.3^{+1.5}_{-1.1}$
$^{156}_{64}Gd_{92}$	1129/1040	$-(14^{+\infty}_{-7})$
$^{170}_{68}Er_{102}$	960/881	1.7(8)
$^{174}_{72}Hf_{102}$	901/809	$-(11^{+\infty}_{-7})$
$^{176}_{72}Hf_{104}$	1227/1138	$\lvert\delta\rvert \geq 4$
$^{178}_{72}Hf_{106}$	1496/1403	$-(0.75^{+0.19}_{-0.17})$
$^{182}_{74}W_{108}$	1257/1157	$-(8.7^{+5.5}_{-2.5})$
$^{232}_{90}Th_{142}$	774/724	$-(1.5^{+2.8}_{-0.7})$

TABLE IIId. Adopted E2/M1 mixing ratios of 2′-2 transitions in transitional and heavy nuclei. In ^{182,184}W the states shown are considered to be γ-type vibrational states.

$^{182}_{74}W_{108}$	1222/1122	$16.7^{+4.1}_{-2.7}$
$^{184}_{74}W_{110}$	903/792	−16.7(5)
$^{186}_{74}W_{112}$	737/615	$-(11^{+4}_{-3})$
$^{186}_{76}Os_{110}$	767/630	$-(50^{+\infty}_{-30})$
$^{188}_{76}Os_{112}$	633/478	$-(23^{+9}_{-5})$
$^{190}_{76}Os_{114}$	557/371	$-(9.2^{+0.8}_{-0.7})$
$^{192}_{76}Os_{116}$	489/283	−4.2(4)
$^{188}_{78}Pt_{110}$	606/340	$-(30^{+30}_{-15})$
$^{190}_{78}Pt_{112}$	598/302	$6.8^{+3.0}_{-1.2}$
$^{192}_{78}Pt_{114}$	612/296	8.84(26)
$^{194}_{78}Pt_{116}$	622/294	19^{+5}_{-3}
$^{196}_{78}Pt_{118}$	688/333	4.8(2)
$^{198}_{80}Hg_{118}$	1088/676	1.14(4)
$^{212}_{84}Po_{128}$	1513/785	0.083(17)
$^{214}_{84}Po_{130}$	1378/769	$3.7^{+2.5}_{-1.4}$

TABLE IVa. Reduced mixing ratios $\Delta_{J_\gamma J_g}$ (defined in Sec. V.B) for gamma to ground-band transitions.

Nucleus	E_γ (keV)	J_γ-J_g	δ	Δ
^{152}Sm	965	2-2g	−9.6(3)	−22.8(7)
	1113	3-2g	−8.7(6)	−23.9(1.6)
	869	3-4	−6.5(3)	−19.8(9)
	1005	4-4	$-(3.1^{+0.3}_{-0.2})$	$-(13.5^{+1.3}_{-0.9})$
^{154}Gd	873	2-2	−9.7(5)	−25.5(1.3)
	1005	3-2	−7.5(4)	−22.9(1.2)
	757	3-4	−5.6(2)	−19.6(7)
	893	4-4	−4.1(4)	−20.3(2.0)
^{156}Gd	1065	2-2	$-(17.5^{+1.6}_{-1.4})$	$-(43^{+4}_{-3})$
	960	3-4	$-(12^{+14}_{-3})$	$-(48^{+56}_{-12})$
	1067	4-4	$-(4.0^{+1.6}_{-0.9})$	$-(19.0^{+7.6}_{-4.3})$
^{160}Dy	879	2-2	−14.8(11)	−40.9(30)
	692	3-2	$-(12^{+3}_{-2})$	$-(36.8^{+9.4}_{-6.3})$
	765	3-4	$-(5.3^{+4.0}_{-1.8})$	$-(21.4^{+16}_{-7})$
^{166}Er	705	2-2	$-(16^{+13}_{-5})$	$-(55^{+45}_{-18})$
	779	3-2	$-(19^{+190}_{-9})$	$-(72^{+720}_{-34})$
	593	3-4	$-(9^{+\infty}_{-5})$	$-(47^{+\infty}_{-26})$
	691	4-4	$-(16^{+27}_{-4})$	$-(108^{+180}_{-27})$
	810	5-4	$-(21.6^{+2.5}_{-2.1})$	$-(149^{+17}_{-15})$
	530	5-6	$-(27^{+8}_{-5})$	$-(227^{+67}_{-41})$
	671	6-6	$-(20^{+90}_{-9})$	$-(204^{+920}_{-92})$
	831	7-6	$-(35^{+9}_{-6})$	$-(367^{+94}_{-63})$
	465	7-8	$-(32^{+98}_{-14})$	$-(387^{+1200}_{-170})$
	645	8-8	$\delta \geq 1.4$ or $\delta \leq -6$	≥ 19 ≤ -83

and collective limits with an average increase of a factor of 100 as compared to the former limit. In the region above $A \sim 60$, the collective limit represents quite well the average trend of the data. Above $A \sim 60$ the B(E2)/B(M1) ratios are 5 orders of magnitude larger than the single-particle values. For an E2 enhancement of 100, the M1 transition probability in these transitions is only 1/1000 of the shell-model strength. This agrees with the collective picture that proton and neutron pairs contribute coherently to the collective motion so that the

TABLE IVb. Reduced mixing ratios $\Delta_{J_\beta J_g}$ for beta to ground-band transitions.

Nucleus	E_γ (keV)	J_β-J_g	δ	Δ
^{152}Sm	689	2-2	19^{+5}_{-4}	73^{+19}_{-15}
	657	4-4	2.1(3)	16.2(2.3)
^{154}Gd	692	2-2	$83.^{+1.5}_{-1.1}$	32^{+6}_{-4}
	677	4-4	3.0(1.3)	22.4(9.7)
	648	6-6	$1.55^{+0.18}_{-0.14}$	$17.8^{+2.0}_{-1.7}$
	612	8-8	$1.2^{+0.4}_{-0.3}$	19^{+7}_{-5}
^{174}Hf	809	2-2	$-(11^{+\infty}_{-7})$	$-(36^{+\infty}_{-23})$
	765	4-4	$-(2.5^{+1.3}_{-0.7})$	$-(16.6^{+8.6}_{-4.6})$
	699	6-6	−0.9(2)	−9.6(2.1)

magnetic moment is aligned with that of the mass to yield a vanishing M1 component.

Clearly, Fig. 1 reveals that collective effects are the dominant feature responsible for the experimental mixing ratios in most even-even nuclei. As one goes higher in A (N and $Z > 28$), the gaps between the closed shells increase and likewise the number of particles in the unfilled shells increases. This increase clearly makes possible greater collective effects as known from B(E2) and as here revealed dramatically by the increase in δ. Possible explanations for the observed M1 transition rates were considered in Sec. III. For deformed nuclei it is interesting to note that the mixing ratios for the beta bands are slightly lower than for the gamma bands. The $B(\mathrm{E2}, 2_\beta^+ \rightarrow 0_g^+)$ values also are generally smaller compared to the single-particle strengths than those for the gamma bands, suggesting that it is the lower E2 strengths of the transitions from the beta bands that lead to the lower δ values.

B. Angular momentum dependence of the E2/M1 mixing ratios in deformed nuclei

The E2/M1 mixing ratios exhibit an inherent angular momentum dependence which stems from the vector coupling coefficients. In the case of gamma to ground-band transitions, an additional spin-dependent contribution arises from the band-mixing corrections to the E2 matrix elements [Eq. (3.36)]. To investigate possible variations in the M1 matrix elements, we present in Table IVa "reduced" mixing ratios Δ defined [see Eqs. (3.40) and (3.41)] by

$$\Delta_{J \rightarrow J_g} = \delta(\mathrm{E2/M1};\ J \rightarrow J_g) / \{ E_\gamma F(J_g, J) \} \ .$$

It appears that for the gamma to ground-band transitions in the nuclei at the beginning of the deformed region as well as for beta to ground-band transitions (Table IVb) there is a decreasing trend in the absolute magnitude of Δ as the angular momentum increases [see Ejiri *et al.* (1971). Unfortunately, the number of measured mixing ratios per nucleus is limited, and the experimental errors are quite large at higher spins. In addition, the E2 transition probabilities cannot be reproduced by a single consistent band-mixing parameter in these nuclei (Hamilton, 1972c).

In ^{166}Er, on the other hand, one has one of the few cases where the band-mixing corrections give a consistent Z_2 parameter. In addition, E2/M1 mixing ratios are available for a whole series of transitions up to spin 8. In contrast to the nuclei at the beginning of the deformed region, the variations of the experimental data for ^{166}Er are not as pronounced. Still, the probability of these reduced mixing ratios being distributed around a constant value is only 0.3%, although most of the contributions to the sum of residue come from only two points; those of the $5-4$ and $7-6$ transitions.

To account for possible deviations from the first-order M1 matrix elements, it might be natural to include the mixing of gamma and ground bands (Lange, 1970), since this was already applied in the case of the E2 matrix elements. This results in a correction factor to the M1 matrix elements of Eq. (3.39) of

$$1 + [J_g(J_g+1) - J_\gamma(J_\gamma+1) + 4] Z_1/2 + J_\gamma(J_\gamma+1) Z_1' \delta_{J_g J_\gamma}/2 \ .$$

(δ here denotes the Kronecker symbol.) The Z_1 parameters arise from the tensorial connection of the M1 to the angular momentum operator [Eqs. (3.28)–(3.30) of Kumar, 1975] and are defined in an analogous way as the Z_2 parameter for the E2 band-mixing corrections.

In the case of $J_\gamma \rightarrow J_\gamma \pm 1$ transitions, the amount of the correction in Z_1 can be derived from the slope of a straight line drawn through the Δ values if they are displayed in the form of Fig. 2. Thereby the theoretical numbers (Baker *et al.*, 1975) which are included for comparison are found to be affected to a large extent. The mixing of the theoretical wave functions was obtained from the adjustment of the Gneuss-Greiner Hamiltonian to the experimental levels of ^{166}Er (Baker *et al.*, 1975), where the angular momentum states were restricted to $J \leq 6$ because of program limitations. An extrapolation to higher spin states reveals even more obviously that the theoretical slope is too high to indicate that the band-mixing effects have been overestimated. This is also observed in the ratio $B(\mathrm{E2};\ 2_\gamma - 2_g) / B(\mathrm{E2};\ 2_\gamma - 0_g)$ (Baker *et al.*, 1975), from which it can be calculated that the theoretical Z_2 parameter is about three times larger than the experimental one.

Even though the probability for the experimental ratios Δ being constant is only 0.3%, no definite linear trend can be observed. Therefore it might be concluded that the gamma-ground-mixing corrections to the M1 matrix elements play only a minor role in the case of ^{166}Er. In fact, since the intraband M1 components are proportional to Z_1, it can be estimated with the aid of the band-mixing amplitude of 10^{-3} and $\delta(\mathrm{E2/M1};\ J_\gamma \rightarrow J_\gamma - 1) \sim 1$ (Reich and Cline, 1970) that the corrections for the $J_\gamma \rightarrow J_\gamma \pm 1$ transitions lie within the experimental errors. In the case of $\Delta J = 0$ transitions there is a slight indication for a nonzero Z_1' parameter, but the experimental errors are still too large to draw a definite conclusion.

C. Comparisons with theoretical calculations for δ(E2/M1) values

Table V gives a comparison of the experimental δ(E2/M1) values (average values from the present survey) with the theoretical values from two theories. The column labeled PPQ refers to the microscopic calculations based on the pairing-plus-quadrupole model (a brief discussion was given in Sec. III. D. 2). The column labeled IBM refers to the nonmicroscopic calculations based on the interacting boson model (Scholten *et al.*, 1978). The IBM may be regarded as an improvement

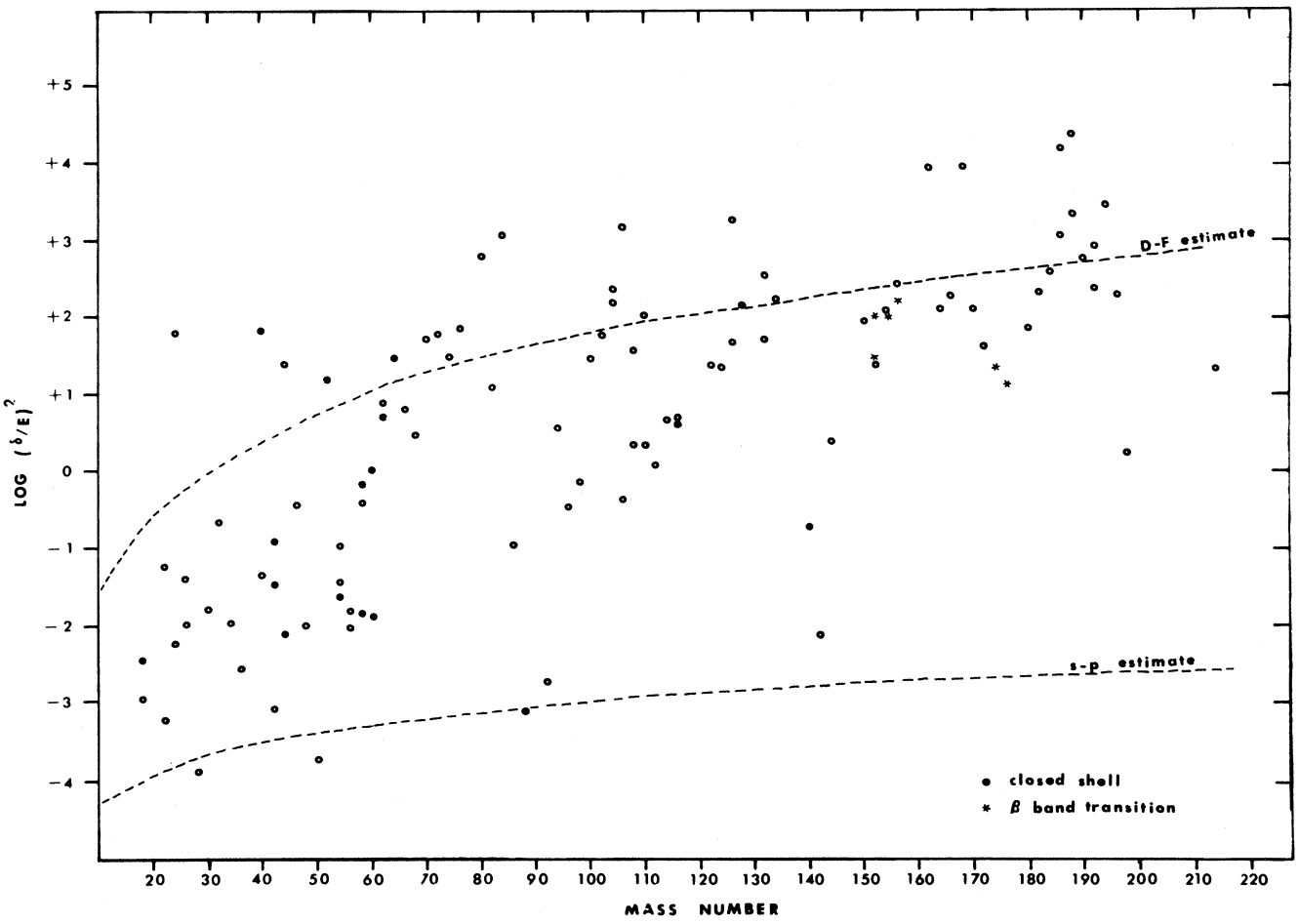

FIG. 1. The log of the square of the δ value from Table III divided by the gamma-ray energy as a function of mass number. The lower dashed curve is the single-particle estimate and the upper dashed curve is the Davydov-Filippov (1958) estimate.

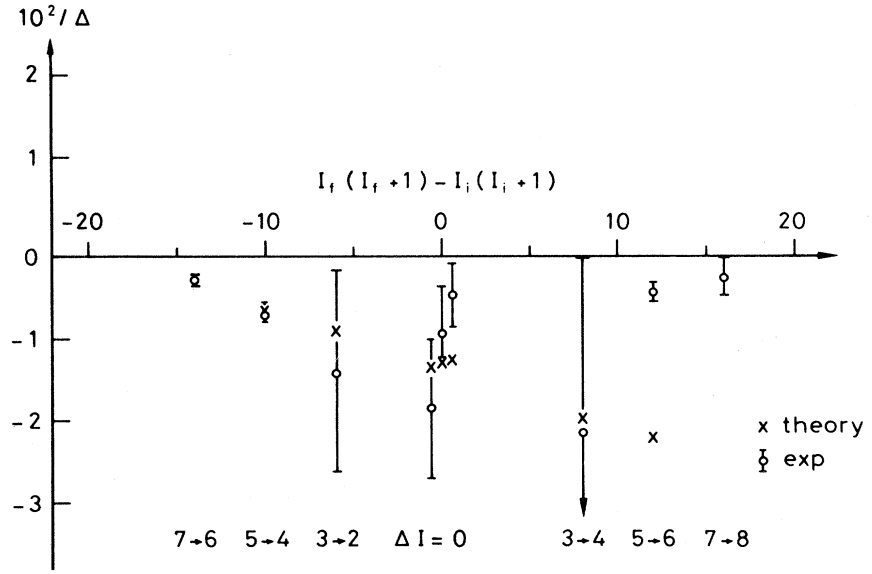

FIG. 2. Angular momentum dependence of the normalized mixing ratio Δ (E2/M1) for $\gamma-g$ transitions in ^{166}Er. The theoretical values are from Baker *et al.* (1975). See Sec. V B for a discussion of these results.

TABLE V. Comparison of experimental and theoretical δ(E2/M1) values, the former from Table I. The experimental γ-ray energy given in column 3 has been used for all the "theory" values.

Nucleus	Transition	E_γ (MeV)	δ (Expt)	δ (Theory) PPQ[a]	IBA[b]
^{150}Sm	$2_\beta \rightarrow 2$	0.712	$-(4.8^{+0.5}_{-0.4})$	−4	−14
	$4_\beta \rightarrow 4$	0.676	−1.3(3)	−10	
	$2_\gamma \rightarrow 2$	0.860	$3.4^{+0.8}_{-0.6}$	58	−3
	$3_\gamma \rightarrow 2$	1.171	$3.6^{+1.7}_{-1.0}$	−221	−12
	$3_\gamma \rightarrow 4$	0.731	$13^{+\infty}_{-7}$	127	−5
	$4_\gamma \rightarrow 4$	0.869	≥ 0.7	33	
^{152}Sm	$2_\beta \rightarrow 2$	0.689	19^{+5}_{-4}	11	22
	$4_\beta \rightarrow 4$	0.657	2.1(3)	4	
	$2_\gamma \rightarrow 2$	0.965	−9.6(3)	−24	−6
	$3_\gamma \rightarrow 2$	1.113	−8.7(6)	−27	−12
	$3_\gamma \rightarrow 4$	0.869	−6.5(3)	−16	−6
	$4_\gamma \rightarrow 4$	1.005	$-(3.1^{+0.3}_{-0.2})$	−10	
^{152}Gd	$2_\beta \rightarrow 2$	0.586	−3.0(3)	−7	
	$2_\gamma \rightarrow 2$	0.765	$4.3^{+0.7}_{-0.6}$	28	
^{154}Gd	$2_\beta \rightarrow 2$	0.692	$8.3^{+1.5}_{-1.1}$	5	
	$4_\beta \rightarrow 4$	0.676	3.0(1.3)	2	
	$6_\beta \rightarrow 6$	0.648	$1.55^{+0.18}_{-0.14}$	1	
	$2_\gamma \rightarrow 2$	0.873	−9.7(5)	−41	
	$3_\gamma \rightarrow 2$	1.005	−7.5(4)	−128	
	$3_\gamma \rightarrow 4$	0.757	−5.6(2)	−80	
	$4_\gamma \rightarrow 4$	0.883	−4.1(4)	−12	
^{156}Gd	$2_\beta \rightarrow 2$	1.040	$-(14^{+\infty}_{-7})$	21	
	$2_\gamma \rightarrow 2$	1.065	$-(17.5^{+1.6}_{-1.4})$	−41	
	$3_\gamma \rightarrow 2$	1.159	$-(8.6^{+4.8}_{-2.3})$	−57	
	$3_\gamma \rightarrow 4$	0.960	$-(12^{+14}_{-3})$	−37	
	$4_\gamma \rightarrow 4$	1.067	$-(4.0^{+1.6}_{-0.9})$	14	
	$2_0 \rightarrow 2$	1.169	0.39(6)	−4	
^{182}W	$2_\beta \rightarrow 2$	1.157	$-(8.7^{+5.5}_{-2.5})$	17	
	$2_\gamma \rightarrow 2$	1.122	$16.7^{+4.1}_{-2.7}$	−5	
^{184}W	$2_\beta \rightarrow 2$	1.275	$28^{+\infty}_{-17}$	−2	
	$2_\gamma \rightarrow 2$	0.793	−16.7(5)	45	
^{186}W	$2_\beta \rightarrow 2$	1.164	13^{+70}_{-6}	−2	
	$2_\gamma \rightarrow 2$	0.615	$-(11^{+4}_{-3})$	−218	
^{186}Os	$2_\gamma \rightarrow 2$	0.630	$-(50^{+\infty}_{-30})$	−15	
	$3_\gamma \rightarrow 2$	0.773	$-(13^{+9}_{-6})$	−14	
^{188}Os	$2_\gamma \rightarrow 2$	0.478	$-(23^{+9}_{-5})$	−10	
	$3_\gamma \rightarrow 2$	0.635	$-(6.9^{+2.9}_{-1.6})$	−11	
^{190}Os	$2_\gamma \rightarrow 2$	0.371	$-(9.2^{+0.8}_{-0.7})$	−8	
	$3_\gamma \rightarrow 2$	0.569	$-9.4^{+1.8}_{-1.2}$	−10	
^{192}Os	$2_\gamma \rightarrow 2$	0.283	−4.2(4)	−5	
	$3_\gamma \rightarrow 2$	0.484	$-(9.2^{+0.9}_{-0.8})$	−5	

TABLE V. (*Continued.*)

Nucleus	Transition	E_γ (MeV)	δ (Expt)	δ (Theory) PPQ[a]	IBA[b]
^{192}Pt	$2_\gamma \rightarrow 2$	0.296	8.84(26)	15	
	$3_\gamma \rightarrow 2$	0.604	−1.82(12)	−2	
	$3_\gamma \rightarrow 2_\gamma$	0.308	7.2(3)	9	
^{194}Pt	$2_\gamma \rightarrow 2$	0.294	19^{+5}_{-3}	20	
^{196}Pt	$2_\gamma \rightarrow 2$	0.333	4.8(2)	−101	

[a]Microscopic calculations based on pairing-plus-quadrupole model [^{150,152}Sm: Kumar (1974); ^{152}Gd: Kumar and Gupta (1978); ^{154}Gd: Kumar *et al.* (1979); ^{156}Gd: Gupta *et al.* (1977); ^{182}W – ^{196}Pt: Kumar (1969)].

[b]Nonmicroscopic calculations based on the interacting boson approximation (Scholten *et al.*, 1978).

over the quasiboson method (see Sec. III. E). Hence a detailed comparison with the results of Bés *et al.* (1963, 1965) is not given here.

The comparison in Table V shows that although the IBM gives better agreement with the magnitudes of the experimental δ values, the PPQ method gives better agreement with the signs. Out of the 8 cases for which a comparison can be made, the IBM gives the wrong sign in 3 cases, while the PPQ does so in only one case.

Table V also shows that the PPQ method allows for a comparison with a much larger number of experimental data. Although there are some disagreements in signs (8 cases out of 46), the agreement in general is surprisingly good. It is surprisingly good because the transition M1 matrix element associated with the cases considered in Table V is typically ±0.01 nm, while the diagonal M1 matrix element (associated with the magnetic moments) is typically 1 nm. Thus the δ values provide extremely sensitive tests of the nuclear wave functions and the magnetic operators. However, there is clear disagreement in the W isotopes. It would be interesting to extend the IBM calculations to the δ values for the W isotopes.

Another nonmicroscopic version of the collective model has been developed [Maruhn-Rezwani *et al.* (1975); see Sec. III. C. 4) where two quadrupole deformation tensors are employed—one for protons and one for neutrons. The δ values of ^{166}Er and this model are given in Table VI. The agreement is quite good in both sign and magnitude, although the experimental errors are large in some cases.

Recently the M1 transitions for three intra-gamma band transitions in ^{168}Er have been measured directly from L subshell conversion electron ratios, rather than deducing them in a questionable way from branching ratios after assuming theoretical values for the E2 components. For the 3^+_γ-2^+_γ, 5^+_γ-4^+_γ, and 6^+_γ-5^+_γ transitions, the measured δ^2 are 2.01(12), 2.45(25), and $3.5(^{1.8}_{0.9})$ (Schreckenback and Gelletly, 1980), respectively. With less accuracy, two of the ^{168}Er δ's have been deduced from γ-ray intensities and are consistent. There are eight other cases of δ^2(E2/M1) extracted from I_γ for intra-γ band transitions in ^{152,154}Gd, ^{162}Dy, and ^{168}Er, and with one exception (0.48) the δ^2 values are between 1.3 and 2.9. Schreckenback and Gelletly (1980) suggest that this constant behavior indicates that a collective effect is responsible for these M1 components. The earlier theory of Greiner (1966), where he introduced different deformations for the neutrons and protons, was found to give very satisfactory agreement with the magnitudes—in particular, the respective theoretical δ^2 values for ^{168}Er are 3.1, 2.8, and 2.7. It would be interesting to apply the more sophisticated Greiner model (Maruhn-Rezwani *et al.*, 1975) to these transitions.

It has been observed recently (Hamilton and Kumar, 1979) that the E2/M1 mixing ratio changes sign upon crossing from "spherical vibrational" ($N \leq 88$) to "deformed rotational" ($N \geq 90$) nuclei in the mass-150 region. The same authors compared the measured values for 18 mixing ratios in ^{150,152}Sm and ^{150,152,154,156}Gd with

TABLE VI. A comparison of the experimental δ(E2/M1) values for ^{166}Er with theoretical ones based on a collective model, as taken from Baker *et al.* (1975).

$J^\pi_\gamma \rightarrow J^\pi_g$	δ_{expt}	δ_{th}
$2^+ \rightarrow 2^+$	$-(16^{+13}_{-5})$	−21.3
$3^+ \rightarrow 2^+$	$-(19^{+190}_{-9})$	−29.8
$3^+ \rightarrow 4^+$	$-(9^{+\infty}_{-5})$	−9.6
$4^+ \rightarrow 4^+$	$-(16^{+27}_{-4})$	−11.4
$5^+ \rightarrow 4^+$	$-(21.6^{+2.5}_{-2.1})$	−22.9
$5^+ \rightarrow 6^+$	$-(27^{+8}_{-5})$	−5.40
$6^+ \rightarrow 6^+$	$-(20^{+90}_{-9})$	−8.0

the predictions of the dynamic deformation model (Sec. III. D. 3). The same theory predicts that the sign changes in δ arise from a sign change in the M1 matrix elements. It would be interesting to extend this type of detailed study to other regions of shape transitions [which, according to the VMI model (Scharff-Goldhaber *et al.*, 1976), occur whenever the energy ratio E_4/E_2 crosses 2.23].

D. Comparison with theoretical calculations for monopole transitions

First let us make some general observations about the q^2 and X values in Table II in relation to general theoretical expectations. As discussed, Rasmussen (1960) pointed out that, since $\rho \sim \langle r^2 \rangle$, one could expect the oscillation of a deformed nucleus about its equilibrium shape to provide a collective contribution to the E0 process. These should then occur for transitions from the β bands but not γ bands because of the K selection rule. The data, as set forth in Table II, indeed show large E0/E2 ratios for $\Delta I = 0$ transitions from all β vibrational states but very small if any from the 2^+_γ states. However, they are not as large for the β-vibrational states as predicted in the rotational model [Eq. (3.29)]. The reductions can be understood in the PPQ model as discussed below. In addition, one sees that in the near-spherical nuclei, $A \geq 184$, the q^2 values for transitions from the second to the first 2^+ states are all very small. Thus, collective enhancements do occur in the β bands.

Table VII compares the experimental X(E0/E2) values with the theoretical values of the PPQ model (Sec. III. D. 2) and those of the RVM (Secs. III. C. 3 and 4). The experimental values follow the general trends of the RVM, where X is quite small for γ-band to g-band transitions compared to β-band to g-band transitions. Thus the X values provide an important check on the band classification of low-energy levels, as pointed out by Rasmussen (1960) and confirmed by Hamilton *et al.* (1964, 1966). However, the *X values cannot be employed as unique "signatures" for β-band members.* They can also be quite large for the decay of two-proton (quasiproton) levels as deduced theoretically for 0^+ states (Kuliev and Pyatov, 1968; Silvestre-Brac and Piepenbring, 1973) and confirmed experimentally in ^{178}Hf (Hamilton *et al.*, 1974). Indeed, the largest known X value (see Table II) for the decay of any 2^+ level in nuclei with $A > 140$ is for the 1276-keV 2^+ quasiparticle level in ^{178}Hf (as earlier noted in Section III. A. 2) [a more detailed discussion is found in Hamilton *et al.* (1974)]. When X exceeds the

TABLE VII. Comparison of experimental and theoretical X(E0/E2) values, the former from Table II.

Nucleus	Transition	E_γ (MeV)	$X^\dagger$ (Expt)	X (theory) PPQ[a]	RVM[b]
^{152}Sm	$2_\beta \rightarrow 2$	0.688	0.41(1)	0.78	1.3
	$4_\beta \rightarrow 4$	0.656	0.58(6)	0.84	1.4
	$2_\gamma \rightarrow 2$	0.964	$5(^{+7}_{-5}) \times 10^{-3}$	10^{-3}	0.0
	$4_\gamma \rightarrow 4$	1.005	$4(2) \times 10^{-2}$	9×10^{-4}	0.0
^{154}Gd	$2_\beta \rightarrow 2$	0.692	0.35(1)	0.75	1.3
	$4_\beta \rightarrow 4$	0.677	0.36(5)	0.70	1.4
	$2_\gamma \rightarrow 2$	0.873	$9(2) \times 10^{-3}$	5×10^{-3}	0.0
^{156}Gd	$2_\beta \rightarrow 2$	1.040	0.56(6)	0.64	1.6
	$4_\beta \rightarrow 4$	1.009	0.71(21)	0.49	1.8
	$2_\gamma \rightarrow 2$	1.065	$8(6) \times 10^{-3}$	10^{-2}	0.0
^{182}W	$2_\beta \rightarrow 2$	1.157	0.094(12)	0.036	0.88
^{184}W	$2_\gamma \rightarrow 2$	0.792	$2(^{+12}_{-8}) \times 10^{-3}$	10^{-2}	0.0
^{188}Os	$2_\gamma \rightarrow 2$	0.478	$4(4) \times 10^{-3}$	2×10^{-4}	0.0
^{190}Os	$2_\gamma \rightarrow 2$	0.371	$1(^{+40}_{-1}) \times 10^{-5}$	5×10^{-5}	0.0
^{192}Pt	$2_\gamma \rightarrow 2$	0.296	$3(^{+5}_{-3}) \times 10^{-5}$	2×10^{-5}	0.0
^{194}Pt	$2_\gamma \rightarrow 2$	0.293	$1.4(5) \times 10^{-4}$	10^{-4}	0.0
^{196}Pt	$2_\gamma \rightarrow 2$	0.333	$3.6(^{+10}_{-8}) \times 10^{-4}$	3×10^{-4}	0.0

[a]Microscopic calculations based on the pairing-plus-quadrupole model [^{152}Sm: Kumar (1974); ^{154,156}Gd: Kumar (1979); ^{182}W – ^{196}Pt: Kumar (1975)].

[b]Rotation-vibration model estimates based on first-order band mixing (see Secs. III. C. 3 and 4). The deformation values are taken from Stelson and Grodzins (1965).

[†]The errors given are in the last significant figures, eg., $3.6(^{+10}_{-8}) \times 10^{-4}$ is $0.00036^{+0.00010}_{-0.00008}$.

TABLE VIII. Comparison of experimental and theoretical ε(E0/E2) values. This quantity equals the square root of the X(E0/E2) value, and the experimental values are taken from the square root of the adopted X values and the signs from q in Table II.

Nucleus	Transition	E_γ (keV)	ε(E0/E2) Expt	ε(E0/E2) Theory
^{150}Sm	$2'\rightarrow 2$	712	±0.20(2)	0.10[a]
^{152}Sm	$2_\beta\rightarrow 2$	688	0.66(4)	0.88[a]
^{182}W	$2_\beta\rightarrow 2$	1157	±0.31(2)	0.19[b]
^{184}W	$2_\gamma\rightarrow 2$	792	±0.05(3)	0.12[b]
^{192}Pt	$2_\gamma\rightarrow 2$	296	±0.006(6)	−0.004[b]
^{194}Pt	$2_\gamma\rightarrow 2$	293	−0.012(3)	−0.010[b]
^{196}Pt	$2_\gamma\rightarrow 2$	333	±0.019(2)	−0.018[b]

[a]Kumar (1974).
[b]Kumar (1975).

TABLE IX. Electric monopole matrix elements, ρ(E0), for $0'\rightarrow 0$ (ground-state) transitions. Percent depletion of the energy-weighted-sum-rule strength for E0 transitions, $2.88A^{5/3}E_{0'}$ (MeV) ρ^2(E0)/Z^2, is also given.

Nucleus	$E_{0'}$ (MeV) Expt	$E_{0'}$ (MeV) Theor	ρ(E0) Expt	ρ(E0) Theor	% Depletion EWSR Expt	% Depletion EWSR Theor	X(E0/E2)	Reference Expt	Reference Theor
^{4}He	20.26		0.55(9)		46(15)			a	
^{10}Be	6.18		0.212(5)		2.3(1)			b	
^{12}C	7.66	7.36	0.71(3)	0.09	20(2)	0.3		b	c
^{14}O	14.00		0.36(8)		5(2)			a	
^{16}O	6.05	6.86	0.37(1)	0.14	3.8(3)	0.5		b	c
	12.05		0.44(1)		10.8(4)			b	
^{18}O	3.63		0.59(6)		7(2)			b	
	5.34		0.27(4)		2.2(7)			b	
^{20}Ne	6.72		0.70(17)		14(8)			b	
	7.19		0.65(13)		13(6)			b	
^{24}Mg	6.43	6.01	0.57(4)	0.1	8(1)	0.3		b	c
	10.716		0.32(6)		5(2)			a	
^{26}Mg	3.59		0.24(2)		0.9(2)			b	
	4.97		0.26(2)		1.6(2)			b	
	6.26		0.58(12)		10(4)			b	
^{28}Si	4.98		0.51(4)		5.0(8)			b	
	6.690		0.15(8)		0.7(6)			a	
^{30}Si	3.79		0.11(1)		0.20(4)			b	
^{32}S	3.78		0.14(1)		0.25(6)			b	
^{34}S	3.91		0.10(1)		0.17(3)			b	
^{36}S	3.35		0.089(1)		0.118(3)			b	
^{38}Ar	3.38		0.22(2)		0.6(1)			b	
^{40}Ca	3.35		0.16(1)		0.30(2)		0.043(4)	b,a	
^{42}Ca	1.84	1.78	0.27(2)		0.51(5)			b	c
^{44}Ca	1.88		0.25(4)		0.5(1)			b	
^{48}Ca	4.28		0.084(3)		0.14(1)			e	
^{58}Ni	19.8(5)		0.7(1)		30(10)			d	
^{64}Zn	18.2(5)		0.7(2)		29(16)			f	
^{66}Zn	18.4(7)		0.7(2)		30(16)			f	
^{70}Ge	1.22		0.09(2)		0.03(2)			e	
^{72}Ge	0.69	0.91	0.081(1)	0.12	0.0158(5)	0.046		e	c
^{72}Se	0.936		0.17(6);0.304(3)**		0.269(5)			a	
^{90}Zr	1.76	1.88	0.070(1)		0.028(1)			e	c
	16.2(5)		1.3(1)		90(20)			f	
^{96}Zr	1.59		0.083		0.04			a	
^{96}Mo	1.1479		0.11(2)		0.05(2)		0.008(2)	a	
^{98}Mo	0.736		0.169(15)		0.07(1)			a	

TABLE IX. *(Continued.)*

Nucleus	$E_{0'}$ (MeV) Expt	Theor	ρ(E0) Expt	Theor	% Depletion EWSR Expt	Theor	X(E0/E2)	Reference Expt	Theor
^{100}Ru	1.1301		<0.089		<0.03		0.011(1)	a	
^{106}Pd	1.133		0.137(25)		0.07(3)		0.014(2)	a	
^{112}Cd	1.2239		0.19(3)		0.14(5)		0.026(4)	k	
	1.4328		0.022(3)*		0.0023(6)		1.0(2)	k	
^{112}Sn	2.1909		<0.15		<0.15		0.046(8)	k	
^{114}Cd	1.134	0.605	0.165(15)	0.069	0.11(2)	0.01	0.026(5)	k	c
	1.305		0.42(3)*		0.008(1)		16(3)	k	
^{114}Sn	1.9530		0.16(4)		0.15(9)		0.042(8)	k	
	2.1562		<0.04*		<0.01		<0.01	k	
^{116}Sn	1.7568		0.066(11)		0.024(9)		0.0086(18)	k	
	2.0273		0.030(3)*		0.006(1)		0.066(11)	k	
	15.6(3)		1.9(3)		180(60)			f	
^{118}Sn	1.7578		0.072(10)		0.030(9)		0.0096(18)	k	
	2.0565		<0.064*		<0.028		0.10(4)	k	
			>0.02		>0.0027			k	
	15.5(6)		≈ 1.7		≈ 150			f	
^{120}Sn	1.8740		0.051(7)		0.016(5)		0.0070(18)	k	
	2.1589		<0.18*		<0.24		0.22(5)	k	
	15.2(5)		≈ 1.9		≈ 180			f	
^{124}Sn	14.8(4)		1.9		186(60)			a	
^{138}Ce	1.4738		0.05—0.15		0.01—0.10		0.063(9)	a	
^{140}Ce	1.902		0.05—0.11		0.02—0.07		0.17	a	
^{144}Sm	14.6(2)		1.8(2)		140(40)			f	
^{150}Sm	0.740	0.815	0.16(5)	0.18	0.07(4)	0.08	0.020(5)	a	g
^{152}Sm	0.685	0.703	0.255(10)	0.22	0.14(1)	0.11	0.07(1)	a	g
^{154}Sm	14.9(3)		1.11(10)		55(15)			f	
^{154}Gd	0.681	0.985	0.284(24)	0.37	0.17(3)	0.42	0.11(3)	a	h
^{156}Gd	1.050	1.234	0.179(17)	0.36	0.11(2)	0.51	0.1	a	h
^{158}Dy	0.991	0.92	>0.063	0.88	>0.012	2.18	0.08(3)	a	l
^{162}Dy	1.400	1.52	<0.04	0.47	<0.007	1.07	0.048(4)	a	l
^{164}Er	1.238	1.123	>0.009	0.14	>0.0003	0.070	0.047	a	c
^{168}Yb	1.156	0.60	>0.0071	1.69	>0.0002	5.15	0.11	a	l
	1.197	0.86	<0.013	-1.32	<0.0006	2.66	0.51	a	l
	1.543	1.60	>0.0055	-0.26	>0.001	0.33	0.76	a	l
^{170}Yb	1.0694	0.71	≤ 0.0071	1.26	≤ 0.0002	3.46	0.0038(4)	a	l
	1.229	0.83	0.14(3)	-1.1	0.08(3)	3.08	0.087(5)	a	l
^{174}Hf	0.828	0.75	0.220(25)	1.3	0.12(3)	3.82	0.18	a	l
^{180}W	0.908	1.05	0.02—0.035	1.1	0.001—0.003	3.83	0.13	a	l
^{184}W	1.0041	1.99	0.019(4)	-0.10	0.0012(5)	0.062	0.006(3)	a	l
^{188}Os	1.086	0.836	0.022	0.093	0.0016	0.022	0.004	a	i
^{206}Pb	1.165		0.034(1)		0.0041(3)			k	
^{208}Pb	13.7(4)	12.3	1.45(15)	0.072	90(20)	0.2		f	j
^{208}Po	1.272		≤ 0.037		≤ 0.0041			k	
			≥ 0.030		≥ 0.0027			k	
^{240}Pu	0.858	0.746	0.13—0.30	0.39	0.04—0.23	0.35	0.05(1)	a	c

*These are for the 0_3^+-0_1^+ transitions. The $\rho(0_3^+$-$0_2^+)$ are much larger in every case.
**Two results are given. [a]Voinova (1976).
[b]Endt (1979a).
[c]Kumar (1980), and unpublished work.
[d]Bertrand *et al.* (1979).
[e]Endt (1979b).
[f]Youngblood *et al.* (1981).
[g]Scholten *et al.* (1978).
[h]Kumar *et al.* (1979).
[i]Kumar and Baranger (1968).
[j]Kumar (1981).
[k]Julin (1979).
[l]Birbrair *et al.* (1975).

β-vibrational limit of $4\beta_0^2(2J-1)(2J+3)/J(J+1)$ for a J-J transition [Eq. (3.29)], one should consider the possibility of proton excitation (Hamilton *et al.*, 1974).

The comparison in Table VII shows that the experimental X values for β-band to g-band transitions are reduced compared to the RVM predictions by a factor of 2–6. The microscopic PPQ model gives most of this reduction but not entirely. In this model anharmonic terms in the potential energy and the mass parameters produce coupling between the rotations and the β and γ vibrations to reduce X. The agreement of the PPQ model values with experiment in ^{152}Sm and ^{154,156}Gd is good (Gupta *et al.*, 1977, Kumar and Gupta, 1978, Kumar *et al.*, 1979). In one case (^{182}W), the $2_\beta \rightarrow 2$ value of the PPQ model is reduced even below the experimental value. This can be ascribed to a too large mixing of the $2_\beta, 2_\gamma$ states in the PPQ model calculation for the W isotopes (the same problem caused the disagreement with the δ values in Table V).

The observed signs of the mixing ratios ε(E0/E2), whose magnitude equals the square root of the X(E0/E2) value and whose sign equals that of the q(E0/E2) value, are compared with theory in Table VIII. Good overall agreement is provided by the pairing-plus-quadrupole model (Kumar, 1974, 1975).

When one considers the smallness of the experimental X(E0/E2; $\gamma \rightarrow g$) values for the $A=190$ region, the PPQ values are quite close. However, completely satisfactory agreement is not obtained there, and a better theory is called for.

A related quantity of interest, which has become available in recent years, is the electric monopole transition matrix element ρ(E0) connecting an excited 0′ state to the ground state. A compilation of such matrix elements, the corresponding transition energies, and of the % depletion EWSR (energy-weighted–sum-rule strength) is given in Table IX. Data are given for the giant monopole states, as well as for the lower 0′ states. Very little of the sum-rule strength goes into the lower 0′ states (excluding very light nuclei). This is in accordance with the basic assumption of the "collective" models (BCS theory, PPQ model, dynamic deformation model, etc.) that the low-energy states are seniority-zero states where all nucleons are paired into time reversally conjugate orbits.

The giant monopole states arise from symmetry breaking and occur at higher energies. The dynamic deformation model has recently been extended to such energies (see the results in Table IX for ^{208}Pb), but the current version does not include such symmetry breaking, and hence the giant monopole strength is not reproduced. On the other hand, the giant quadrupole does not require such symmetry breaking, and the corresponding sum rule strength is reproduced (Kumar, 1981), but the strength distribution is not correct because of some other problems.

The dynamic deformation model also has been extended to nuclei as light as ^{12}C. The comparison in Table IX shows that while the model reproduces the energies of the first 0′ states extremely well, the calculated ρ(E0) values are too small for the light masses. This discrepancy, coupled with good agreement with the E2 and M1 moments discussed elsewhere, suggests that two quasiparticle states with nonzero seniority need to be included for a better description and that the E0 operator is particularly sensitive to admixtures of such a state.

Results of the IBM for the $0' \rightarrow 0$ transitions are not available for most of the cases in Table IX, with the exceptions of ^{150,152}Sm. For these two cases, the IBM reproduces the experimental ρ values quite well. However, one model parameter was employed to fit the E0 transitions (Scholten *et al.*, 1978).

The ρ(E0) values calculated by Birbrair *et al.* (1975), who combined Migdal's theory with the Nilsson model and with the pairing-plus-quadrupole model, are too large by an order of magnitude.

In conclusion, another example of the current importance of measurements of E0/E2 and E2/M1 mixing ratios is found in the work on shape coexistence discovered in the lightest known mercury nuclei, $^{184-188}$Hg, very far from stability [see the reviews of Hamilton (1976) and (1979)]. Deformed bands built on low-lying 0^+ states (in ^{184}Hg only 7 keV above the first 2^+ level) with much larger deformation than the ground band are observed in ^{184,186,188}Hg. The 0^+ states were established by their E0 decays to the ground states. The 2^+ and 4^+ members of the bands built on these well-deformed 0^+ levels are found to have significant E0/E2 admixtures in their decays to help establish their different deformations.

In the odd-A nuclei in this region, clear differences are observed when one studies, for example, the $h_{9/2}, h_{11/2}$ bands where the $h_{9/2}$ particles are coupled to oblate Hg cores, while the $h_{11/2}$ hole states are coupled to the more nearly spherical Pb cores to provide important tests of particle-core-coupling models (Collins *et al.*, 1982; Zganjar, 1980). Even more fascinating is the unique possibility—for example, in ^{189}Tl or others of the lighter odd-A Tl isotopes—to study the same particle state built on both oblate and prolate structures in the same odd-A nucleus by coupling to the oblate ground state and more deformed prolate excited band in ^{188}Hg. Ground-state coupling has been observed. Indeed, in ^{189}Tl a band which has the right energy to rise from the coupling to the excited prolate deformed band in seen (Zganjar *et al.*, 1981). Based on the E0 admixtures seen in the $\Delta I=0$ transitions between the weak oblate and strong prolate deformed structures in ^{188}Tl, such an E0 admixture is considered a signature of such coexistence in ^{189}Tl. The K conversion coefficient of the $\Delta I=0$ transition from the new excited band in ^{189}Tl is much larger than the theoretical E2 value but is unfortunately consistent with M1. Thus one needs a multipole mixing ratio measurement of the gamma decay to establish whether this transition is E2 + E0 or essentially pure M1. A new on-line He refrigeration system being developed will be necessary to carry out such studies with heavy ions [see J. H. Hamilton (1981) for more details]. Thus in this way, too, E0/E2 and E2/M1 mixing ratios are providing cru-

cial data to test nuclear models in exotic regions of the periodic table.

ACKNOWLEDGMENTS

We would like to thank R. Soundranayagam for his help in the calculations of the X values in Table II. This work was supported in part by grants from the National Science Foundation and the U. S. Department of Energy, Contract No. DE-AS05-76ER05034-M008. One of us (J.L.) would like to express thanks for the generous hospitality he enjoyed during several stays at Vanderbilt University. He also is indebted to the Deutsche Forschungsgeminschaft for a travel grant.

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