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M1 Transitions in Even-Even Deformed Nuclei and the IBA

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In the simplest form of collective vibrational and rotational models, M1 transitions are forbidden because the leading term of the collective M1 operator is proportional to the total nuclear angular momentum, which is a good quantum number. Nevertheless, a considerable amount of data exists on M1 components in transitions between collective states in even-even deformed nuclei, and numerous efforts have been made to interpret their origin. Two basic sources of such components can be postulated involving either admixtures of quasiparticle excitations, such as $K^{\pi}=1^{+}$ bands, or a collective mechanism. Recent experimental studies (Schreckenbach and Gelletly, 1980) of the M1 components in intraband transitions in the gamma bands of several deformed nuclei have indicated a remarkable constancy in the empirical E2/M1 mixing ratios. A further analysis of the transitions in ^{168}Er (Warner et al., 1981) has indicated that this constancy applies also to the absolute M1 strengths involved, and that these strengths are at the level of 8×10^{-4} s.p.u. The existence of such small and constant M1 strengths in several nuclei argues strongly against an interpretation based on admixtures of a hypothetical $K^{\pi}=1^{+}$ band, since the energy and interaction matrix elements of such a band would be expected to vary considerably from nucleus to nucleus, being dependent on the particular Nilsson orbits available.

The adoption of a collective mechanism to explain the M1 transitions must involve the inclusion of higher order terms in the M1 operator, coupled with the assumption of a vectorial nature for the collective g-factor. The study of Schreckenbach and Gelletly (1980) showed that the theory of Greiner (1966), for example, which generates a dependence of the g-factor on the axis of rotation by assuming different deformations for the proton and neutron cores, reproduces the data for the gamma-band transitions excellently. A collective mechanism also suggests that M1 transitions in deformed nuclei should be describable within the framework of the Interacting Boson Approximation.

In IBA-1, the leading order term of the M1 operator is proportional to $(d^{+}d)^{(1)}$ which is in turn proportional to the angular momentum operator. Hence, as in the pure collective picture, no M1 transitions can occur in this order. Including the next order terms the operator becomes (Scholten et al., 1978):

$$T(M1) = (g_B + \alpha N)\,\hat{L} + \beta[\hat{T}(E2) \times \hat{L}] + \gamma n_d \hat{L}. \qquad (1)$$

Here g_B is the effective boson g-factor, N is the number of bosons, and $\hat{T}(E2)$ and n_d are the E2 and d-boson number operators respectively.

The first term of eq. (1) is still diagonal and does not contribute to transitions. The M1 transition matrix element becomes:

$$\langle \chi I_f | T(M1) | \chi' I_i \rangle = \gamma \sqrt{I_i(I_i+1)(2I_i+1)} \langle \chi I_f | n_d | \chi' I_i \rangle \, \delta_{I_i I_f}$$

$$- \beta \, f(I_i, I_f) \langle \chi I_f | T(E2) | \chi' I_i \rangle \qquad (2)$$

where $$f(I_i,I_f) = \left\{ \frac{1}{40} (I_i+I_f+3)\,(I_f-I_i+2)\,(I_i-I_f+2)\,(I_i+I_f-1) \right\}^{1/2} \qquad (3)$$

Note that the third term of eq. (1) is diagonal in L and hence only gives a contribution to transitions between states of the same spin. Thus, for $I \pm 1 \rightarrow I$ transitions, eq. (2) leads to a particularly simple expression for the reduced E2/M1 mixing ratio, namely

$$\Delta(E2/M1) = -1/\{\beta \, f(I_i, I_f)\} \qquad (4)$$

where Δ is related to the measured multipole mixing ratio δ by

$$\delta(E2/M1) = 0.835 \, E_\gamma (\text{in MeV}) \, \Delta(E2/M1) \qquad (5)$$

The spin dependence represented by eq. (3) is identical to that produced by any of the geometrical models discussed above, including, in fact, the assumption of $\Delta K=1$ admixtures. Such a conclusion is hardly surprising, since Grechukhin (1963) has derived the identical expression in the geometrical framework, in a totally analogous way, by treating the nuclear excitation spectrum as one of boson type quadrupole excitations. The various approaches differ only in the parameterization of the constant β, which depends on the specific assumptions made concerning the dynamics of the nuclear collective motion. Thus, for example, the results of Schreckenbach and Gelletly (1980) for intraband transitions in the γ band, obtained with the model of Greiner (1966), can be reproduced exactly in the IBA-1 basis by appropriate choice of the constant β.

In the IBA formalism, the inclusion of both s and d bosons, and the finite boson number, give rise to the additional contribution in eq. (2) for $I \rightarrow I$ transitions, which involves the matrix element of n_d. The corresponding M1 matrix element thus, in principle, depends on the relative sizes and signs of the two terms of eq. (2). However, it can be noted that the n_d operator is proportional to the E0 operator in the IBA, and hence the corresponding matrix elements will be vanishing small for $\gamma \rightarrow g$ or $\gamma \rightarrow \gamma$ transitions, but significant for $\beta \rightarrow g$ transitions. Conversely, the E2 matrix element will be considerably larger for $\gamma \rightarrow \gamma$ or $\gamma \rightarrow g$ transitions, than for the $\beta \rightarrow g$ transitions. The absolute values of the constants of eq. (2) have been determined from the data on ^{168}Er. The constant β can be determined uniquely from the empirical $\Delta(E2/M1)$ values of the intraband transitions in the γ band. Using this value, the absolute strengths of the $I \rightarrow I$ $\beta \rightarrow g$ transitions, measured to be essentially pure M1, can be used to extract γ. This analysis indicates that, in the case of $\gamma \rightarrow g$ and $\gamma \rightarrow \gamma$ transitions, the first term of eq. (2) is $\lesssim 1\%$ of the second. For $\beta \rightarrow g$ transitions, the second term is $\lesssim 10\%$ of the first. Thus in practice, the two terms are independent and the conclusions reached above concerning the spin dependence of $I \pm I \rightarrow I$ transitions from the γ band hold also for $I \rightarrow I$ transitions. For $\beta \rightarrow g$ M1 transitions the spin dependence indicated by the n_d dependent term is again identical to that which can be deduced from the geometrical model (Kumar, 1975). In this respect, it is important to note that since n_d is a scalar, its matrix elements are independent of L in the limit of infinite N. If the corresponding $\beta\to g$ E2 transition is now assumed to be described by the leading order intensity relations, i.e.:

$$<\chi I_g|T(E2)|\chi' I_\beta> = <I_\beta 020|I_g 0> <I_g||T(E2)||I_\beta> \qquad (6)$$

the inclusion of the analytic expression for the Clebsch-Gordan coefficient of eq. (6) again yields the spin dependence of eq. (3) for Δ(E2/M1). Thus this spin dependence, in both the IBA and geometrical models, is appropriate for all M1 transitions from the β and γ bands.

The signs of the Δ(E2/M1) values can also be considered. For $\gamma\to g$ (and $\gamma\to\gamma$) transitions, the sign will be constant as long as the sign of β is constant. Similarly, for $\beta\to g$ transitions, the sign will be determined by γ. Thus in well deformed nuclei, where the two parameters can be expected to vary only slightly, one expects a constant sign for all $\gamma\to g$ transitions, and a constant, but possibly opposite, sign for all $\beta\to g$ transitions. The review of Krane (1973) indicates that this is indeed observed in the majority of cases, $\gamma\to g$ Δ values being negative and $\beta\to g$ values being positive in the adopted sign convention. In transitional regions, the underlying physical description of the two constants may cause the signs (and magnitudes) of the two terms to vary more rapidly.

Finally, a comment can be made concerning the extension of the arguments presented here to the region of Pt nuclei, where the O(6) quantum numbers (σ,τ,ν_Δ) are valid (Casten and Cizewski, 1978). In such a case, the $\hat{n}_d$ term of eq. (2) obeys the selection rule $\Delta\sigma=2$, $\Delta\tau=0$, while the E2 operator obeys the rule $\Delta\sigma=0$, $\Delta\tau=\pm1$. Thus for transitions in ^{196}Pt, for example, between the σ=N-2 and N groups of levels, the $\Delta\tau=0$, $I\to I$ transitions might be expected to be dominantly M1 in character, with relative absolute strengths distributed according to the spin dependence of the first term of eq. (2). In addition the ratio of these M1 transitions to M1 branches involving $\Delta\sigma=2$, $\Delta\tau=\pm1$ should be large. Unfortunately, insufficient data are available at present to test these predictions.

To conclude, it has been shown that the IBA can produce essentially identical results for M1 transitions in deformed even-even nuclei as can be obtained from the geometrical approach, and many comparisons with experiment are already available for the latter in the literature. Since no physical constants are involved in the IBA-1 formalism, it would be useful to use the similarity of the two approaches to obtain a physical description of the IBA constants. Use of the IBA-2 approach might also prove illuminating, since it should identify the contributions of the neutron and proton degrees of freedom, analogous to the method of Greiner.

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