Search for Higher Order Effects in Allowed β Transitions*

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The β-γ directional correlations of several allowed β transitions with unusually large ft values ($\log ft>7$) were measured. Effects of second-forbidden β components are expected to manifest themselves in small observable anisotropies if second-forbidden matrix elements are not reduced appreciably by those nuclear-structure effects that cause the reduction of the allowed matrix elements. The experimental results for the anisotropy factor $A_{22}(W)$ in the β-γ directional correlation function $W(\theta)=1+A_{22}(W)P_2(\cos\theta)$ are: $Na^{22}(W_0=1.69,\ \log ft=7.4)$; $A_{22}(\bar{W}=1.8)=-0.001\pm0.005$; $Co^{56}(W_0=3.88,\ \log ft=8.6)$, $A_{22}(\bar{W}=3.3)=-0.001\pm0.003$; $Sb^{124}(W_0=2.23,\ \log ft=7.7)$, $A_{22}(\bar{W}=2.0)=+0.002\pm0.003$; $Cs^{134}(W_0=2.3,\ \log ft=8.9)$, $A_{22}(\bar{W}=1.9)=+0.001\pm0.003$; $Tb^{160}(W_0=2.1,\ \log ft=8.1)$, $A_{22}(\bar{W}=1.9)=+0.013\pm0.007$. Except for the highly deformed Tb^{160}, no evidence of interference effects with second-forbidden β components was found, indicating that whatever the mechanism that reduces the allowed matrix elements it somehow also reduces the second-forbidden matrix elements. The small anisotropy found in Tb^{160} may be a result of some K selection rule effect or may be caused by a competing forbidden β transition. Evidence for the existence of such a β transition (which, however, is very difficult to fit into the established Tb^{160} decay scheme) is given.

I. INTRODUCTION

In the usual theory of allowed beta decay, only s-wave leptons are considered and the β-γ directional correlation of allowed β transitions is thus expected to be isotropic. Under certain conditions, however, the contributions from p- and d-wave leptons may become large enough to cause measurable effects, e.g., the shape of the β spectrum may show deviations from the statistical distribution or the β-γ directional correlation may display a small anisotropy. These higher order effects are mainly due to the interference between s waves and p or d waves and are, therefore, characterized by the presence of cross-terms of the allowed matrix elements $\int 1$ or $\int \boldsymbol{\sigma}$, and the second-forbidden matrix elements $\int i\boldsymbol{\alpha}\cdot\mathbf{r}$, $\int i\gamma_5\mathbf{r}$, $\int \boldsymbol{\alpha}\times\mathbf{r}$, $\int r^2$, $\int \boldsymbol{\sigma}r^2$, $\int(\boldsymbol{\sigma}\cdot\mathbf{r})\mathbf{r}$, R_{ij}, T_{ij}, A_{ij}, and S_{ijk}. The contributions of the first three matrix elements are of the order $v_N pR$, where v_N is the average nucleon velocity, p is the β-particle momentum and R is the nuclear radius, all in units $m=\hbar=c=1$. The remaining second-forbidden matrix elements give contributions of the order $(pR)^2$. Since the nuclear radius $R=3.4\times10^{-3}A^{1/3}$ is considerably smaller than unity, measurable effects are only expected if $p\gg1$ or if the ordinary allowed matrix elements are strongly reduced by some nuclear-structure effect that is not operative for at least some types of second-forbidden matrix elements.

If, for argument's sake, a nuclear model is assumed where the nuclear matter is uniform (wave function independent of r), the following approximate relations between second-forbidden and allowed matrix elements are obtained[1,2]:

$$\int r^2\approx\tfrac{3}{5}R^2\int 1\,, \tag{1}$$

$$\int \boldsymbol{\sigma}r^2\approx\tfrac{3}{5}R^2\int \boldsymbol{\sigma}\,, \tag{2}$$

$$\int (\boldsymbol{\sigma}\cdot\mathbf{r})\mathbf{r}\approx\tfrac{3}{5}\eta R^2\int \boldsymbol{\sigma}\,, \tag{3}$$

where η is a factor that depends on the angular properties of the nuclear wave function.

In the nonrelativistic limit (i.e., discarding the small components of the nuclear wave functions) the additional relations can be obtained[1,2]:

$$\int i\boldsymbol{\alpha}\cdot\mathbf{r}\approx\mp\frac{3}{20}\Lambda\alpha ZR\int 1\,, \tag{4}$$

$$\int i\gamma_5\mathbf{r}\approx\frac{1}{2M}\int \boldsymbol{\sigma}\mp\frac{3}{20}\Lambda\alpha ZR\eta\int \boldsymbol{\sigma}\,, \tag{5}$$

$$\int \boldsymbol{\alpha}\times\mathbf{r}\approx\frac{1}{M}(1+\mu_p-\mu_N)\int \boldsymbol{\sigma}\,, \tag{6}$$

where M is the rest mass of a nucleon. The factor $\Lambda\approx1\pm(W_0\mp2.5)A^{1/3}Z^{-1}$ is close to unity, except for light nuclei. For medium heavy nuclei $R\approx1.5\times10^{-2}$ and the matrix elements $\int r^2$ and $\int \boldsymbol{\sigma}r^2$ give, in general, very small contributions. The strongly model-dependent factor η, however, can be large. Thus $\int(\boldsymbol{\sigma}\cdot\mathbf{r})\mathbf{r}$ and $\int i\gamma_5\mathbf{r}$ could give observable contributions, i.e., deviations of one percent or more from the characteristics of ordinary allowed β transitions.

Relations (4) and (6) are relatively insensitive to nuclear model assumptions. Equation (6) is based on the conserved vector-current theory[3,4] and involves the

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difference $\mu_p - \mu_N$ of the anomalous magnetic moments of the nucleons. Although the factor $(1+\mu_p-\mu_N)/M = 2.5\times 10^{-3}$ is comparatively large, the relative contribution of $\int \boldsymbol{\alpha}\times\mathbf{r}$ is not expected to increase substantially even if $\int \boldsymbol{\sigma}$ is much reduced as a result of nuclear-structure effects.

The second- and third-rank tensor components characterized by the matrix elements A_{ij}, T_{ij}, R_{ij}, and B_{ijk}, respectively, have a small influence on the spectrum shape or on the β-γ directional correlations and are discarded.[1]

In the following, only the strongly model-dependent second-forbidden matrix elements are taken into account. Within this approximation, the anisotropy factor A_{22} in the allowed β-γ directional correlation

$$W(\theta)=1+A_{22}(W)P_2(\cos\theta) \tag{7}$$

can be expressed as a function of the nuclear structure dependent parameter η. Assuming a β transition $I_i \rightarrow I$ followed by a pure 2^L-pole gamma transition $I\rightarrow I_f$, the anisotropy factor is

$$A_{22}(W)=A_2(W)F_2(LLI_fI)\,, \tag{8}$$

$$A_2(W)=\frac{\{\mp(\alpha Z/10R)(2\Lambda-3)+(2/15)(W_0-W)+(6/25)W\}\eta R^2(p^2/W)F_2(11I_iI)}{(1+(3/40)\Lambda\eta(\alpha Z)^2)^2\pm\alpha ZR[-\frac{1}{3}(5W+1/W)+\frac{1}{10}(\Lambda-4)(W_0-W)\eta+\frac{1}{10}\Lambda\eta(p^2/W)]}. \tag{9}$$

The upper (lower) sign applies to $\beta^-(\beta^+)$ transitions. This equation has been derived considering only the most prominent possible contributions of second-forbidden components if the $\int\boldsymbol{\sigma}$ matrix element is reduced. The contribution of the Fermi component $\int 1$ has been neglected. In most allowed transitions $|\int 1|^2 \ll |\int\boldsymbol{\sigma}|^2$.[5] Furthermore, the Fermi component does not lead to terms that contain η. The expression for $A_2(W)$ is similar to the one given by Morita,[1] except that higher order terms are included for the use with large values of η. Equation (9) gives a reasonably good estimate of the anisotropy for $|\eta|\gg 1$ and $|\eta|<200$.

If η is of the order ten or larger, the anisotropy should be observable. We assume an average ft value of $10^{4.5}$ for "normal" allowed β transitions. Thus, if the ft value of a β transition is $10^{6.5}$ or larger, the $\int\boldsymbol{\sigma}$ matrix element is reduced by a factor of ten or more and in such hindered transitions, η could be of the required magnitude.

Several attempts have been made to observe anisotropies in beta-gamma directional correlations involving hindered allowed β transitions. Steffen[6] reported vanishing anisotropies ($|A_{22}|<0.0005$) for Na^{24}($\log ft = 6.1$), Sc^{46}($\log ft=6.2$) and for Co^{60}($\log ft=7.3$). In Na^{22}($\log ft=7.4$), a very small anisotropy, $A_{22}=-0.0018\pm0.0003$, was observed. Later measurements seemed to indicate sizable anisotropies (a few percent) in the β-γ directional correlation of Na^{22}, Co^{56}($\log ft=8.6$) and Mn^{56}($\log ft=7.2$).[7–10] It is the purpose of this paper to present new data on several allowed β transitions with very high ft values and to clear up the situation where conflicting data have been reported.

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II. EXPERIMENTAL METHODS

The β-γ directional correlation measurements were performed with a β-γ coincidence spectrometer. The β-detector, a 2-mm thick Li-drifted silicon detector operated at room temperature, was mounted in a Lucite vacuum chamber (Fig. 1). As far as β-energy selection is concerned, the only criterion important for the present measurements is the rejection of β particles below a certain energy. Therefore, back scattering in the β detector which presents a serious limitation of solid state detectors for ordinary β-γ directional correlation measurements is of no importance here. An integrally mounted 3-in.$\times$3-in. NaI(Tl) crystal served as detector for the gamma radiation.

The measurements on Sb^{124} were performed with the previously described β-γ directional correlation equipment,[11] using a $\frac{1}{8}$-in. thick plastic scintillator as β-detector.

The beta sources which were deposited on 1 mg/cm^2 Mylar foils, were thin enough to completely neglect scattering effects at the β energies measured.

Special attention was devoted to the correction of the observed coincidence data for the unavoidable contributions from γ-γ coincidences and in some cases,

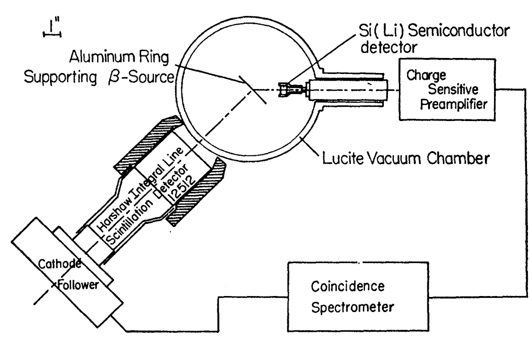

FIG. 1. Beta-gamma directional correlation equipment.

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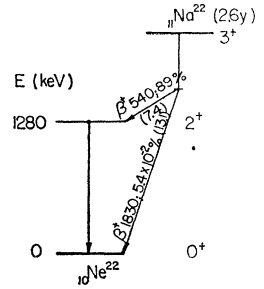

FIG. 2. Decay of Na^{22}.

e^--γ coincidences. The relative γ-γ coincidence contributions were in no case larger than 0.02. However, in view of the small β-γ anisotropies to be expected, the γ-γ coincidence background for each case was very carefully evaluated. In this connection, the solid-state β detector was not found to be superior to plastic scintillator detectors in spite of the often claimed insensitivity of Si β detectors to γ radiation.

The anisotropy factor $A_{22}(W)$ of the β-γ directional correlation was determined from the measured and corrected β-γ coincidence rate observed at different angles θ. Corrections for the β-inner bremsstrahlung directional correlations[12] were considered and were found to be negligible in most cases.

III. EXPERIMENTAL RESULTS

Na^{22}

The well-known allowed positron decay of Na^{22} to the 1.28-MeV excited state of Ne^{22} (Fig. 2) has a large ft value ($\log ft=7.4$). If the second-forbidden matrix elements are not appreciably reduced, η is of order 30, and the expected anisotropy factor for $W=1.8$ is according to Eq. (9): $A_{22}\simeq\pm0.0004$.

The β-γ directional correlation of Na^{22} was measured, accepting positrons in the energy range from 0.20 to 0.54 MeV. After applying corrections for all spurious effects, an anisotropy value of $A_{22}=-0.001\pm0.005$ was obtained.

This value is consistent with the result $A_{22}=-0.0018\pm0.0003$, reported by Steffen.[6] The larger anisotropy reported by Subba Rao[7] ($A_{22}=-0.015\pm0.003$) could not be confirmed.

Co^{56}

The positron decay of the 77-day Co^{56} has been well investigated (Fig. 3). The 1.5-MeV β^+ transition to the 2.09-MeV 4^+ excited state of Fe^{56} is allowed. Its ft value, however, is unusually high for an allowed transition ($\log ft=8.7$). Thus, contributions from second-forbidden matrix elements may be expected. If the second-forbidden matrix elements are not affected by whatever effect that causes the allowed matrix elements to be small, the nuclear structure factor $|\eta|$ is of order 120. The anisotropy factor expected for this $4(\beta^+)4(\gamma)2$ cascade is then $A_{22}(W=3.0)\simeq\pm0.04$. Pettersson *et al.*[8] reported an experimental anisotropy factor $A_{22}=+0.015\pm0.004$ for $W>3.0$. Somewhat smaller, yet nonvanishing, anisotropies were reported by Müller[9] and Daniel *et al.*[10]

For the measurement of the Co^{56} β^+-γ directional correlation, the beta-energy window was set to accept positrons in the energy range from 1.00 to 1.45 MeV. The gamma detector accepted the 1.24-MeV photopeak. Although several gamma transitions of energies >1 MeV following the electron capture decay of Co^{56} precede the 1.24-MeV gamma transition, their detection probability for the solid-state β counter is small enough to keep the corrections for γ-γ coincidences very small. The experimental result for the anisotropy factor after correcting for all interfering effects is $A_{22}=-0.001\pm0.003$.

This result disproves the existence of large observable contributions of second-forbidden matrix elements to the allowed β^+ decay of Co^{56}. The result indicates that the nuclear-structure factor must be smaller than ten: $|\eta|<10$. This result implies that not only the allowed matrix elements, but also the second-forbidden matrix elements which could contribute to this transition, are greatly reduced.

Sb^{124}

The 0.620-MeV β transition ($\log ft=7.7$) proceeds between the 3^- ground state[13] of Sb^{124} and the 3^- 2.295-MeV excited state of the daughter nucleus Te^{124} (Fig. 4). The 3^- spin-parity assignment to the 2.295-MeV excited state is well established on the basis of conversion coefficient measurement of the strong 1.69-MeV transition[14] and the 1.69–0.603-MeV γ-γ directional correlation measurements.[15,16] In this case, for

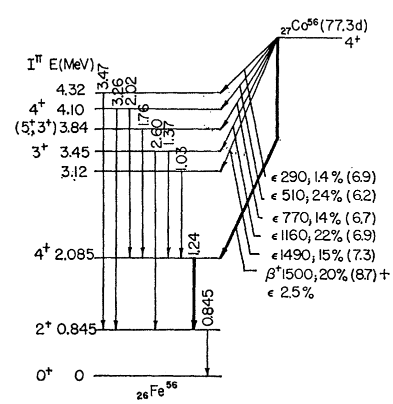

FIG. 3. Decay of Co^{56}.

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measuring the 0.620–1.69-MeV β-γ correlation as a function of the beta energy, the $\frac{1}{8}$-in. thick Pilot B scintillation crystal was used as a β-detector and the analyzers were set on 50-keV intervals in the energy range 250–600 keV. The results obtained for the channels below 400 keV and where the highest energy channel was used, were corrected for the small γ-γ coincidence background. Values of $A_{22}(W)$, as a function of the energy of the β particles, vanish consistently for the entire energy range. Taking the weighted average of these values:

$$A_{22}(1.5<W<2.2)=+0.0021\pm0.0025.$$

This experimental result limits the values of η to $-15<\eta<5$. From the ft value of the β transition, one would expect $|\eta|$ to be of the order 40.

Cs^{134}

The β transition of interest ($W_0=0.656$ MeV; $\log ft=8.9$) occurs between the 4^+ ground state of Cs^{134} and the 1.402-MeV excited state in Ba^{134} (Fig. 5). The spin $I=4$ for the Cs^{134} ground state has been uniquely determined using the atomic beam magnetic resonance method.[17] The value of the magnetic moment obtained from this measurement favors a $(g_{7/2},d_{3/2})$ proton-neutron configuration; hence, the positive parity assignment for this level. The 4^+ spin-parity assignment of the 1.402-MeV excited state in Ba^{134} is based on γ-γ directional correlation,[18] γ-γ polarization correlation[19,20] and conversion coefficient[21] measurements. The spin assignment has been indirectly confirmed by β-γ circular polarization correlation experiments.[22,23] Thus, the 0.656-MeV β transition is an allowed β transition. The ft value of this β transition is uncommonly large

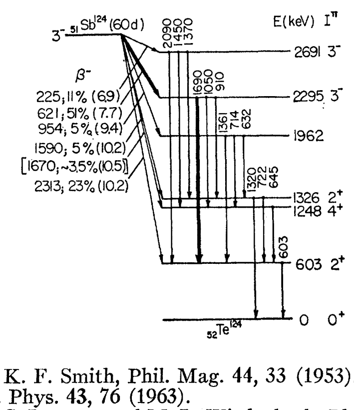

FIG. 4. Decay of Sb^{124}.

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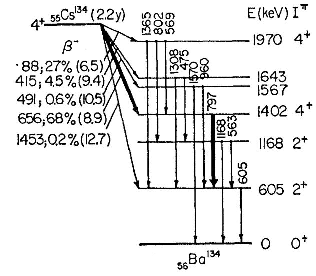

FIG. 5. Decay of Cs^{134}.

($\log ft=8.9$). This large ft value can be understood on the basis of the shell model. The β transition involves mainly a $d_{3/2}$ neutron (with some $s_{1/2}$ admixture and very small $d_{5/2}$ and $g_{7/2}$ admixtures) transforming into a $g_{7/2}$ proton (with some $d_{5/2}$ and very small $d_{3/2}$ admixture). The allowed transitions can thus only proceed through small admixtures, whereas the transition between the main components $d_{3/2}\rightarrow g_{7/2}$ corresponds to a second-forbidden β decay. This type of a second-forbidden β transition is observed in Cs^{137} and has a $\log ft$ value of 11.9. A comparison with the ft value of the 0.656-MeV β transition ($\log ft=8.9$) of Cs^{134} indicates that the contribution of second-forbidden components to this allowed β transition are expected to be about 3% (in intensity). This contribution corresponds to $|\eta|\cong160$. The same η value is obtained if the ft value of the 0.656-MeV β transition is compared to the nominal value ($\log ft=4.5$) for ordinary allowed β transitions. The expected β-γ directional correlation factor is $A_{22}=+0.005$ for $\eta>0$ and $A_{22}=-0.05$ for $\eta<0$.

The 0.656–0.797-MeV β-γ directional correlation has been previously reported as being isotropic within the limit of about 2%.[24–26] The present experiment gives for the anisotropy factor $A_{22}(1.8<W<2.0)=+0.001\pm0.003$. The energy window in the β channel was carefully chosen to reject any conversion electrons in coincidence with the 0.797-MeV γ radiation.

The second-forbidden matrix elements interfering among themselves could give rise to a $P_4(\theta)$ term in the β-γ correlation function, if the γ radiation has a multipolarity of $L=2$ or higher. Since the square of the second-forbidden matrix elements in the Cs^{134} β transition is expected to be of the order of a few percent, a nonvanishing A_{44} may exist. For this reason, an effort was made to find evidence of a $P_4(\theta)$ term. The experimental result, however, indicates a vanishing $P_4(\theta)$ term, $A_{44}=+0.001\pm0.006$.

Thus, the experimental results on the strongly hindered, allowed 0.656-MeV β transition of Cs^{134} again indicate that the second-forbidden matrix elements are smaller than expected from simple ft value considerations.

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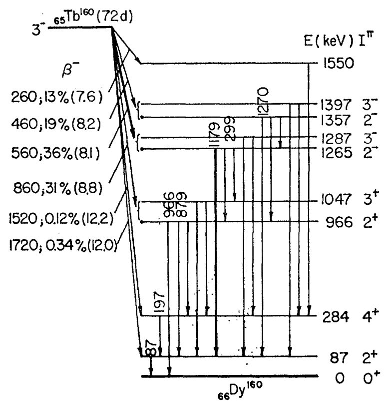

FIG. 6. Decay of Tb^{160}.

Tb^{160}

The spin of the Tb^{160} ground state ($I=3^-$) has been measured directly[27] and the odd-parity assignment follows from the $\frac{3}{2}^+[411]$ proton state and the $\frac{3}{2}^-[521]$ neutron state which are the most plausible orbitals for this deformed nucleus. According to the generally accepted decay scheme, as shown in Fig. 6, the 0.56-MeV β-transition mainly feeds the 1.265-MeV excited state in Dy^{160}. The spin-parity of this level must be 2^- based on the $E1$ multipolarities of the 1.18-, 0.298-, and 0.216-MeV transitions.[28] This spin assignment has been confirmed by nuclear orientation experiments,[29] and by gamma-gamma directional correlation measurements.[30]

We have measured the 0.560–1.18-MeV β-γ directional correlation in order to get information about the $3^-\rightarrow 2^-$ allowed beta transition ($\log ft=8.1$). The result obtained, in terms of the A_{22} coefficient in the directional correlation function, is

$$A_{22}=+0.013\pm0.007.$$

From the $\log ft$ value $|\eta|\cong 70$ is obtained, and Eq. (9) gives $A_{22}=-0.001$ for $\eta>0$ and $A_{22}\approx-0.07$ for $\eta<0$. The anisotropy is not sensitive even to large changes of the value of η (if $\eta>0$). From the decay scheme of Tb^{160}, it is easy to see that independent information on the 0.560-MeV beta transition can be obtained by measuring the 0.560–0.298-MeV β-γ directional correlation. This measurement was performed and the result, corrected for the contribution from the coincident background measured by shifting the γ window, is

$$A_{22}=-0.070\pm0.009.$$

These two results are inconsistent with the decay scheme, as presented in Fig. 6, where the 1.180-MeV and 0.298-MeV transitions both depopulate the same 1.265-MeV excited level and both are pure electric-dipole transitions connecting 2^- and 2^+ states. In the first, as well as in the second measurement, the beta-channel accepted β particles in the energy interval 450–560 keV. A study of the gamma-ray spectrum observed with a high-resolution Ge(Li) semiconductor detector[31] (full width at half maximum = 5.5 keV) did not reveal any unknown gamma transitions and did not help to elucidate the problem. On the basis of already available data, it is difficult to assign a spin sequence for the 1.180- and 0.298-MeV gamma transitions that is different from the $2^-\rightarrow 2^+$ sequence.[32] It does not seem likely that $\sim$10% contribution from the 0.54–1.20-MeV β-γ cascade can alter the result for 0.56–1.18-MeV β-γ correlation significantly.

In view of the uncertainty regarding the decay scheme of Tb^{160}, the possibility exists that the small anisotropy observed in the 0.560–1.180-MeV β-γ directional correlation may be caused by a competing β-γ cascade, involving a first-forbidden β transition. It is difficult, however, to incorporate such a β transition into the decay scheme. If the observed anisotropy is entirely due to the 0.560–1.180-MeV β-γ directional correlation and if the 0.560-MeV β transition is, indeed, allowed, the nonvanishing anisotropy factor may be due to K-forbiddenness of the allowed β transition. In such a case, the second-forbidden matrix elements may be expected to have their normal values and could contribute to the beta-gamma anisotropy.

Before any definite conclusions can be reached, the decay scheme of Tb^{160} must be re-examined. Measurements designed to clarify the level structure of Dy^{160} are in progress.

IV. SUMMARY AND CONCLUSIONS

In all cases, except Tb^{160}, the anisotropies of the β-γ directional correlations involving allowed, but hindered, β transitions were found to be zero, within limits of error. In most cases, a measurably large anisotropy would have been expected from the contribution of second-forbidden beta-components that were computed from $\log ft$-value considerations. The experimental results indicate that whatever mechanism is responsible for the strong reduction of the allowed matrix elements also reduces the second-forbidden components.

The results on the presumably allowed 0.560-MeV β transition of Tb^{160} are inconclusive, because the measurements revealed inconsistencies in the generally accepted decay scheme of this isotope.

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