Nuclear matrix elements governing the 693 keV first-forbidden beta transition in the decay of ^{111}Ag

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Energy dependence of the $1/2^-$(693 keV β)$3/2^+$(342 keV γ)$1/2^+$ angular correlation was measured with a fast-slow scintillation spectrometer. The data was used in conjunction with the other available experimental observables to determine the beta matrix elements, employing Buhring's formalism as modified by Simms. The sizes of the matrix elements indicate a "cancellation effect." It was observed that the vector matrix element ratio A_{CVC} was consistent with the conserved vector current prediction based on the fact that the Coulomb Hamiltonian is diagonal. However, contributions from off-diagonal matrix elements of the Coulomb Hamiltonian could not be rules out. The structure of the involved levels is discussed on the basis of the single particle shell model and the one-quasiparticle-phonon coupling model.

[RADIOACTIVITY ^{111}Ag; measured $\beta\gamma(\theta)$, deduced nuclear matrix elements.]

I. INTRODUCTION

^{111}Ag is a spherical odd proton nucleus ($Z=47$) which decays by beta emission to ^{111}Cd. The decay scheme is well established[1] and is shown in Fig. 1. The beta transition of present interest is the one with $\frac{1}{2}^- \rightarrow \frac{3}{2}^+$ spin sequence and an end-point energy of 693 keV leading to the 342 keV excited state of ^{111}Cd. This is indicated in the decay scheme by bold lines.

The ξ ($=\alpha Z/2\rho$) value for this beta group is ≈ 11.6. The beta end-point energy, $W_0=2.3$ is in m_0c^2 units. Hence, in this case the criterion for the applicability of the ξ approximation, namely, $\xi >> (W_0-1)$, seems to be well fulfilled. It is therefore expected that this transition would follow the ξ approximation. In fact, Hamilton *et al.* and Seshagiri Rao[3] reported nearly isotropic angular correlation for the present beta-gamma cascade, indicating the applicability of the ξ approximation. The shape of this 693 keV beta branch was first measured by Robinson and Langer[4] with a 4π anthracene spectrometer. They found a large deviation from the allowed shape amounting to about 17%. Such a large shape deviation, along with the rather large logft value of 7.8,[5] suggests cancellation among matrix elements governing this decay, thus indicating clearly a break-down of the ξ approximation. Later measurements of Lehmann[6] and Nagarajan *et al.*[7] yielded a statistical shape for this beta transition, supporting the validity of the ξ approximation. Recently, Seshi Reddy *et al.*[8] remeasured the spectrum shape of this transition with an intermediate-image spectrometer used in coincidence with the cascading gamma radiation and reported a deviation from a statistical shape factor of about 9%. The contradictory results thus reported on the spectrum shape factor for this beta group make the situation rather confusing. However, the improved technique used in Ref. 8 makes that result more reliable. Thus, a 9% shape deviation is incompatible with such small β-γ anisotropies reported earlier.[2,3]

The beta-gamma circular polarization correlation was measured by Delabaye *et al.*[9] On the basis of the extreme single-particle model, they calculated the matrix elements for this transition and found that the results were compatible with the ξ approximation except for the spectrum shape reported by Robinson and Langer.[4]

Seshagiri Rao[3] extracted the nuclear matrix

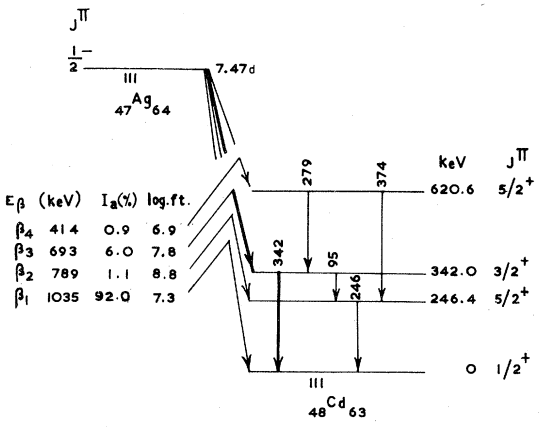

FIG. 1. Partial decay scheme of the ground state decay of the ^{111}Ag as taken from Ref. 1. The β-γ cascade of present interest is shown by bold lines.

elements (NME's) on the basis of his angular correlation results together with other experimental observables. He obtained sets of NME's which support neither the ξ approximation nor the modified B_{ij} approximation and classified the transition an "intermediate approach." However, he assumed the validity of Fujita's theoretical estimate for the ratio between two of the vector matrix elements, based upon the conserved vector current (CVC) theory. In Fujita's theory[10,11] the off-diagonal elements in the Coulomb Hamiltonian (H_{Coul}) are neglected. Damgaard and Winther[12] suggested that this approximation is not always valid and pointed out that the off-diagonal matrix elements in H_{Coul} might sometimes be significant and in some cases have been observed (see Refs. 13–16). Hence, Fujita's estimate for Λ_{CVC}, the vector-matrix element ratio $\int\vec{\alpha}/\int i\vec{r}/\rho$, cannot be used in the analysis for obtaining matrix elements. A more rigorous analysis avoiding the restriction of the CVC theory is expected to yield useful information not only on the NME's contributing to this beta transition but also about the higher-order matrix elements that are important in this case.

Hence, it was felt necessary to reanalyze the experimental data for the matrix elements of the 693 keV beta transition in ^{111}Ag. For this, a remeasurement of the energy dependence of the β-γ directional correlation was also made. While interpreting the results, applicability of the quadrupole-phonon quasiparticle coupling model[17] was also tested together with the shell model predictions.

II. EXPERIMENT

The fast-slow scintillation assembly used in the present work was described in our earlier papers.[18–20] In the same references, one finds details about the standardization of the setup, source preparation, data collection, analysis of the experimental data, and various corrections to be applied to arrive at the final values of the β-γ correlation coefficients at different beta energies.

A carrier-free ^{111}Ag sample was obtained from the Bhabha Atomic Research Centre, Bombay, in the form of silver nitrate in dilute nitric acid. The experimental film source was prepared and the correlation experiments were conducted as described in Refs. 18–20. The angular correlation results are summarized in Fig. 2. Here the angular correlation function $\epsilon(W)$ is the product $A_2(\beta)\times A_2(\gamma)$, normalized so that $A_0(\beta)A_0(\gamma)=1$.

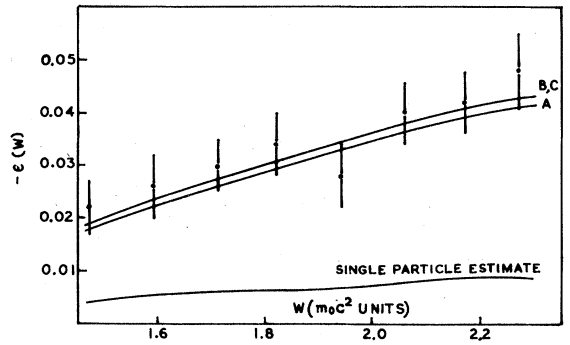

FIG. 2. Energy dependence of the 693 keV beta 342 keV gamma directional correlation function $\epsilon(W) = A_2(\beta)A_2(\gamma)$, normalized so that $A_0(\beta)A_0(\gamma)=1$. The spikes are the experimental points. The smooth curves represent the theoretical predictions of $\epsilon(W)$ for the matrix element parameter set A, B, and C given in Table II. The single particle estimate of $\epsilon(W)$ is also shown in the figure.

III. EXTRACTION OF NUCLEAR MATRIX ELEMENTS

The $\frac{1}{2}^-$ (693 keV beta)$\frac{3}{2}^+$ transition is governed by the four zeroth-order matrix elements of tensor ranks 1 and 2 besides the corresponding higher-order matrix elements arising out of the finite size of the nucleus. In order to determine the four NME parameters x_0, u_0, Y, and z_0, the following experimental data were analyzed:

(a) beta-gamma directional correlation coefficients $\epsilon(W)$ of the present work(Fig. 2),

(b) spectrum shape factor $C(W)$ from Ref. 8,

(c) beta-gamma circular polarization as a function of angle, $P_\gamma(\theta)$ due to Delabaye *et al.*[9]

The NME parameters as defined by Smith and Simms[21] are given in our earlier work.[22] Buhring's formalism[23] as modified by Simms[21] was employed for the various experimental observables. In the analysis x_0, u_0, and Y are expressed relative to z_0, which in turn is estimated from the logft value.

The MATCAL computer search program was adapted to obtain the NME parameters. The parameters of the ERWF's were computed from Bhalla and Rose tables.[24] The initial coarse search yielded the following ranges for the NME parameters: $-4.0 \leq x_0 \leq -1.0$, $-2.0 \leq u_0 \leq 0.0$, $-2.0 \leq Y \leq 0.5$. The fine search finally restricted the magnitudes of the NME parameters to such narrower ranges: $-3.0 \leq x_0 \leq -0.15$, $-1.0 \leq u_0 \leq -0.1$, $-1.2 \leq Y \leq -0.15$, and $z_0 = 1.0$.

A. Higher-order matrix elements and the CVC ratio

The CVC prediction of Fujita[10] and Eichler[11] is given by

$$\Lambda_{CVC}^{0}=(W_0-2.5)\rho+2.4\xi\rho, \tag{1}$$

where $\xi(=\alpha Z/2\rho)$ is the Coulomb energy and W_0 is the end-point energy. The CVC prediction as modified by Damgaard and Winther[12] (DW) is given by

$$\Lambda_{CVC}^{DW}=\int\vec{\alpha}\Big/\int\frac{i\vec{r}}{\rho}=\Lambda_{CVC}^{0}+\tfrac{1}{2}\alpha z(0.6-\lambda), \tag{2}$$

where $\lambda=x'/x$ in the notation for the NME parameters used by Simms.[21]

If the parameter $\lambda=0.6$, $\Lambda_{CVC}^{DW}=\Lambda_{CVC}{}^{0}$, and

$$\int\vec{\alpha}\Big/\int\frac{i\vec{r}}{\rho}=D'y/x. \tag{3}$$

The connection between Λ_{CVC}^{expt} and x_0, u_0, and Y can be deduced as

$$\Lambda_{CVC}^{expt}\equiv\frac{D'y_0}{x}=\left[\frac{DY}{x_0(1+0.8a)}+\frac{D(x_0+u_0)}{x_0(1+a)}\right]+\frac{DY(0.8a)}{x_0(1+0.8a)}+\frac{D(x_0+u_0)d}{x_0(1+a)}\lambda. \tag{4}$$

The parameter λ was determined by equating Λ_{CVC}^{DW} [Eq. (2)] and Λ_{CVC}^{expt} [Eq. (4)] for each set of solutions x_0, u_0, z_0, and Y. This was a part of the computer program, and the range of λ values thus obtained corresponding to the experimentally obtained sets of NME parameters is given in Table I. In the same table the ranges of x, u, Y, and $D'y_0$ are summarized, and the numerical values of the constants ρ, a, d, and D are given. The values of Λ_{CVC}^{expt} are also included in this table. Three typical sets, A, B, and C were chosen from the ranges of the NME parameters given in Table I with minimum χ^2 values and are furnished in Table II. The theoretical values of $\epsilon(W)$, $C(W)$, and $P_\gamma(\theta)$ are shown in Figs. 2–4, corresponding to these sets along with the experimental values. The energy dependence of the β-γ circular polarization correlation was predicted for the typical sets at three angles and is shown in Fig. 5.

Λ_{CVC}^{expt} is shown as a function of λ in Fig. 6 for the limiting values of Λ_{CVC}^{expt} given by sets A and C (Table II). The variation of Λ_{CVC}^{DW} due to Damgaard and Winther [Eq. (2)] is also furnished as a function of λ in the same figure. Λ_{CVC}^{expt} plots intersect the Λ_{CVC}^{DW} plot yielding limiting values of λ as $\lambda_{min}=-0.8$ and $\lambda_{max}=1.66$. These values are in good agreement with the theoretical limits given in Table II.

TABLE I. Extracted NME parameters and NME's of the 693-keV beta transition in ^{111}Ag corresponding to $D=0.1870$, $d=-0.2185$, $a=-0.050\,53$, $\rho=0.014\,99$, and $\xi=11.684$.

NME parameters	Absolute values of NME's
$z_0=1.0$	
$x=-0.19$ to -2.67	$\left\lvert\int\frac{iB_{ij}}{\rho}\right\rvert=0.108\pm0.073$
$u=-0.19$ to -0.82	
$D'y_0=-0.125$ to -0.627	$\left\lvert\int\frac{i\vec{r}}{\rho}\right\rvert=0.079\pm0.038$
$Y=-0.2$ to -1.0	
$\eta=0.130\pm0.087$	$\left\lvert\int\frac{\vec{\sigma}\times\vec{r}}{\rho}\right\rvert=0.026\pm0.009$
$\Lambda_{CVC}^{expt}=D'y_0/x=0.45\pm0.21$	$\left\lvert\int\vec{\alpha}\right\rvert=0.025\pm0.003$
$\lambda=-0.80$ to $+1.66$	

B. Scaling factor η and the evaluation of absolute values of NME's

The scaling factor η was obtained from a knowledge of the ft value, x_0, u_0, and Y following the procedure suggested by Smith and Simms.[21b] The ranges of the absolute values of the matrix elements corresponding to the NME parameters given in Table I are also included in the same table. The values of the matrix elements for the typical sets given in Table II are presented in Table III. In the evaluation of $\int iB_{ij}/\rho$ (the rank-2 matrix ele-

TABLE II. Typical matrix element parameter sets for the 693 keV beta transition in ^{111}Ag obtained from the range given in Table I.

Set	z_0	x_0	u_0	x	u	$D'y_0$	DY	Y	λ	Λ_{CVC}^{expt}
A	1.00	−2.00	−0.40	−2.06	−0.41	−0.48	−0.17	−0.9	1.66	0.23
B	1.00	−2.40	−0.80	−2.47	−0.82	−0.58	−0.17	−0.9	1.64	0.24
C	1.00	−0.20	−0.20	−0.19	−0.19	−0.13	−0.037	−0.2	−0.80	0.66

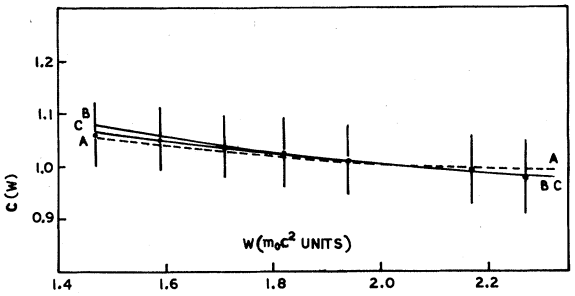

FIG. 3. Shape correction factor $C(W)$ vs W (in m_0c^2 units) as taken from Ref. 8 along with the theoretical predictions due to the NME parameter sets A, B, and C given in Table II.

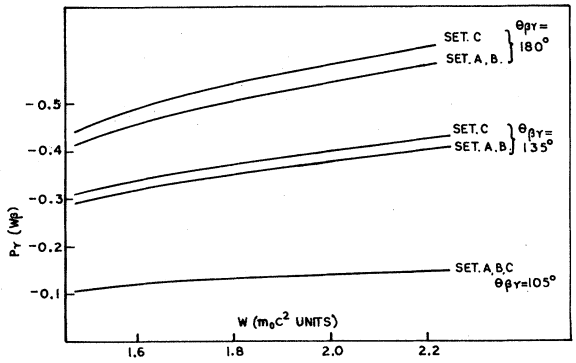

FIG. 5. Theoretical energy dependent β-γ circular polarization correlation for the matrix element sets A, B, and C at angles 105°, 135°, and 180°.

ment), z_0 is taken as z, since the higher-order matrix element z' occurs in z_0 with a relatively small coefficient ($a=-0.05$). The maximum error thus introduced is only about 5%. The contributions of the third-forbidden matrix element parameters r', s', and t' are reduced by a factor of $D'R$ (=0.0028 for the present case). Thus, in order that r', s', and t' contribute to the transition significantly, they must be at least $1/D'R$ (≈357) times as great as the largest of the first-forbidden matrix element parameters. The smallest value of η for the present case in η_{min} =0.0429. The largest possible value of the third-forbidden NME parameters is $\sqrt{2}/\eta_{min}$ (≈32.96), which is greater than the first-forbidden NME parameters by only one order of magnitude. The third-forbidden NME parameters must be greater by at least about two orders of magnitude of the first-forbidden NME parameters in order to be of significance in the analysis. Thus, it is seen that practically no significant error is introduced as a result of neglecting the third-forbidden NME parameters. The matrix elements that arise out of screening effects are important only at very low beta energies and hence are not considered in the present analysis.

C. Discussion

The NME parameters reported in Table I are significantly different from those reported by Seshagiri Rao.[3] This is due to the fact that no restriction was imposed on the CVC ratio in the present analysis.

The experimental value of the vector-matrix-element ratio Λ_{CVC}^{expt} from the present analysis varies between 0.23 and 0.66, while the corresponding values of λ range from −0.8 to 1.6. From the range of values of Λ_{CVC}^{expt}, a value of 0.42, which is predicted on the basis of Fujita's theory,

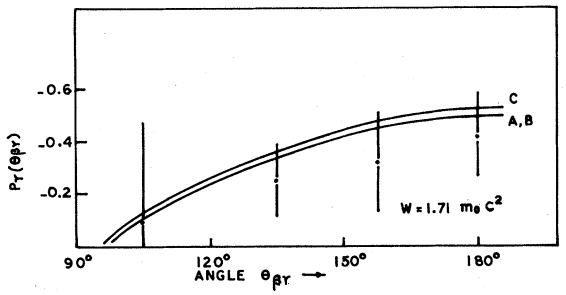

FIG. 4. Angular dependence of the β-γ circular polarization as taken from Ref. 9 along with the theoretical predictions corresponding to the NME sets given in Table II.

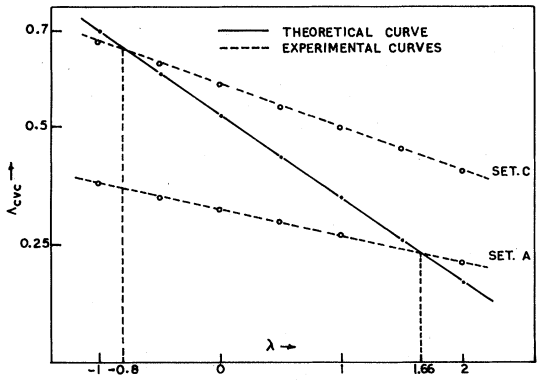

FIG. 6. CVC ratio (Λ_{CVC}) vs $\lambda(=x'/x)$. Λ_{CVC}^{expt} are due to the two limiting sets of solutions A and C given in Table II for NME parameters. Λ_{CVC}^{DW} are from Eq. (2) and Λ_{CVC}^{expt} are from Eq. (4).

TABLE III. Values of nuclear matrix elements for the typical sets given in Table II.

Set	η	$\int \frac{iB_{ij}}{\rho}$	$\int \frac{i\vec{r}}{\rho}$	$\int \frac{\vec{\sigma}\times\vec{r}}{\rho}$	$\int \vec{\alpha}$
A	0.049	0.041	−0.101	0.017	−0.024
B	0.047	0.039	−0.117	0.030	−0.028
C	0.217	0.181	−0.041	0.034	−0.027

cannot be ruled out in the present analysis. Thus Λ^0_{CVC} due to Fujita falls within the range of the present experimental values. The value of λ due to Fujita is 0.6, which lies in the experimental range given above. Thus, in the present case, the limits on the parameter λ are consistent with the assumption that the nuclear Coulomb Hamiltonian is diagonal. However, since λ can be as large as 1.6, significant contributions to the vector-matrix-element ratio from the off-diagonal matrix elements of the Coulomb Hamiltonian cannot be ruled out as in the case of 2^-(959 keV β)2^+ (412 keV γ)0^+ cascade in ^{198}Au.[25]

From Tables I and II, it is seen that there is no domination of the $\int iB_{ij}$ matrix element and that some of the matrix elements (Y and u) are reduced from their normal size. The fact that $\int iB_{ij}$ is reduced excludes the operation of any selection rule effect. The j-selection rule cannot be applied inasmuch as the transforming proton and neutron in the present case are not in the same major shell. Furthermore, the K-selection rule cannot be invoked in view of the fact that ^{111}Cd is not in the deformed region. Hence, both the rank 1 and rank 2 tensor matrix elements could cause this particular beta decay. For the applicability of the ξ approximation, DY must be very much larger than the NME parameters x, u, and z. But as seen from Table II the values of DY are of the same order of magnitude as the other NME parameters. Thus the condition for cancellation effect, namely

$$|\xi Y| \gtrsim |x| \sim |u| \sim |z|, \tag{5}$$

is satisfied here. This suggests that a cancellation effect in rank 1 matrix elements can explain the failure of the ξ approximation in the present case. This inference is slightly at variance from that of Seshagiri Rao[3] who suggested an intermediate approach between the ξ approximation and the cancellation effect.

D. Structure of the involved levels

^{111}Ag is a spherical odd-proton ($Z=47$) which decays to ^{111}Cd. The neutron and proton configurations of ^{111}Ag are $50+(2d_{5/2})^6\,(1g_{7/2})^6\,(3s_{1/2})^2$ and $28+(2p_{3/2})^4\,(1f_{5/2})^6\,(2p_{1/2})^1\,(1g_{9/2})^8$, respectively.

Delabaye *et al.*[9] in their attempt to study the structure of the 342 keV excited state in ^{111}Cd assumed a wave function of the type

$$|J,M\rangle = \alpha\,|d_j;\ J=j,M\rangle + \beta\,|s_{1/2},\ J_c=2,J,M\rangle, \tag{6}$$

in which the first part corresponds to the single-particle excitation and the second part corresponds to the core excitation. The first part of the wave function is assumed to be due to the excitation of the particle into the $d_{5/2}$ orbit. The latter part of the wave function corresponds to the retention of the particle in the $s_{1/2}$ orbit and exciting the core to the first phonon vibrational state. The relative amplitudes of these wave functions are denoted by α and β.

For the ^{111}Ag ground state, in the lowest seniority approximation ($\nu=1$),

$$|J',M'\rangle = |P_{1/2},J'=\tfrac{1}{2},M'\rangle. \tag{7}$$

Though the detailed description of the $\nu=3$ member of the wave function (6) may be rather complicated, the reduced nuclear matrix elements of the 693 keV beta transition are composed of only single-particle matrix elements.

$$\langle J=\tfrac{3}{2}||T_{KL\gamma}||J'=\tfrac{1}{2}\rangle = \alpha a_k \langle p_{1/2}||T_{KL\gamma}||d_{3/2}\rangle + \beta' b_k \langle p_{3/2}||T_{KL\gamma}||s_{1/2}\rangle. \tag{8}$$

The operators $T_{KL\gamma}$ are defined in Ref. 26. The a_k and b_k are decoupling coefficients.[27] β' is the amplitude of the $|s_{1/2},\ (p_{1/2},\ p_{3/2})_{J_c=2};J,M\rangle$ proton-excitation component in the wave function of Eq. (6). In the approximation of the wave function of Eq. (7), only this component contributes to the matrix elements of Eq. (8).

With this description, Delabaye *et al.*[9] calculated the nuclear matrix element ratios, which are independent of the coefficients α and β', and obtained the following results:

$$x=-0.84,\ z=-0.63 \text{ (taking } u=1).$$

Normalizing with respect to z (i.e., $z=1$),

$$x=1.333,\ u=-1.5873.$$

These values are not in agreement with the experimentally obtained matrix element ratios.

The analysis of Delabaye *et al.*, however, showed that the values of the matrix elements were not sensitive to α and β' in Eq. (8). This implies that, in this simple case, the information given by the nuclear parameters does not permit a distinction between the single particle and core-excitation mechanisms.

It is expected that the Kisslinger and Sorensen[17] model might describe better the levels involving the present beta transition. Using a quasiparticle-phonon coupling scheme, Kisslinger and Sorensen represented the ground state of ^{111}Ag by the following wave function:

$$|\tfrac{1}{2}\rangle = 0.73\,|0_{\frac{1}{2}\frac{1}{2}}\rangle + 0.38\,|2_{\frac{5}{2}\frac{1}{2}}\rangle + 0.45\,|2_{\frac{3}{2}\frac{1}{2}}\rangle. \quad (9)$$

The 342 keV $\frac{3}{2}^+$ excited state of ^{111}Cd is represented as

$$|\tfrac{3}{2}\rangle = -0.61\,|0_{\frac{3}{2}\frac{3}{2}}\rangle + 0.38\,|2_{\frac{7}{2}\frac{3}{2}}\rangle + 0.05\,|2_{\frac{5}{2}\frac{3}{2}}\rangle - 0.34\,|2_{\frac{3}{2}\frac{3}{2}}\rangle - 0.53\,|2_{\frac{1}{2}\frac{3}{2}}\rangle. \quad (10)$$

With these wave functions, the beta decay matrix elements are evaluated following the generalized formalism due to Behrens and Bühring.[28] The "partial" form-factor coefficients for the single particle transitions encountered in the present case are calculated and are then used to compute the form factors and the matrix element ratios given in Tables IV and V. Table V also includes the matrix element ratios obtained by Delabaye *et al.*[9] on the basis of the single-particle model, along with those from the present experimental analysis. The following inferences could be drawn from an inspection of Table V:

(i) The single-particle predictions of Delabaye *et al.* for the matrix element ratios are not in good agreement with the present experimental ratios.

(ii) Even the quasiparticle picture, in this case, is not satisfactory in fitting the experimental observables. This was as expected by Kisslinger and Sorensen, who pointed out that in the region below the Sn isotopes, the general coupling scheme seems to be adequate only for cases in which at least one kind of particle is near the 28, 38, 40, or 50 closed shell.

TABLE IV. Form-factor coefficients of the beta transition ^{111}Ag → ^{111}Cd calculated by using the quasiparticle model.

$V_{F_{110}}^{(0)}$	$A_{F_{111}}^{(0)}$	$V_{F_{101}}^{(0)}$	$A_{F_{211}}^{(0)}$
−1.37	1.70	0.000	−0.49

They traced the discrepancy in the appearance of low-lying $\frac{7}{2}^+$ states in nuclei (which in a pure shell model would be described as having three or five particles, or holes in the $g_{9/2}$ level) to either three quasiparticle states playing an important role or a strong quadrupole interaction making necessary a quite different coupling scheme. But, for the other levels in isotopes with $Z < 50$ and $N \geq 50$, such as Ag isotopes, it is expected that this method will give a good description. However, from the present work it is found that the one-quasiparticle calculations are quite inadequate in explaining the beta decay from the ground state of ^{111}Ag to the 342 keV state of ^{111}Cd. A three-quasiparticle picture might yield a better description for the levels involved in the present beta transition, as was the conjecture of Kisslinger and Sorensen for the low-lying $\frac{7}{2}^+$ states for the isotopes in this region.

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TABLE V. Comparison of the experimentally determined matrix element ratios with the predictions of a single-particle calculation and a quasiparticle calculation governing the 693 keV β of ^{111}Ag.

Matrix element ratio	Single particle[a] prediction	Present quasiparticle calculations	Results from the present experimental analysis	
			Set *A*	Set *B*
$\int \frac{i\vec{r}}{\rho} \Big/ \int \frac{iB_{ij}}{\rho}$	1.60	−1.68	−2.47	−2.96
$\int \frac{\vec{\sigma}\times\vec{r}}{\rho} \Big/ \int \frac{iB_{ij}}{\rho}$	1.59	−2.46	0.41	0.82

[a] These results are due to Delabaye *et al.* (Ref. 9).

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