Tests of pseudospin symmetry via Coulomb excitation measurements on ^{187}Os and ^{189}Os

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(Received 11 April 1997)

Coulomb excitation measurements on ^{187}Os and ^{189}Os have been carried out, using beams of α particles, with the aim of measuring $B(E2)$ values for transitions between states in the low-lying bands. The results are compared with predictions in a pseudospin symmetry scheme and, in the case of ^{189}Os, are used to extract two-state mixing amplitudes for states in near degenerate bands. [S0556-2813(97)04309-4]

PACS number(s): 25.70.De, 21.60.Ev, 23.20.Js, 27.70.+q

I. INTRODUCTION

Odd-mass nuclei in this mass region are notoriously difficult to understand and although ^{187}Os and ^{189}Os have been studied using various reactions (e.g., neutron capture [1,2], single-particle transfer [3,4]) the structure of their low-lying states is by no means clear. Previous interpretations using the Nilsson model [5,6] have met with a certain degree of success. More recently, an in-depth analysis of ^{189}Os [2] in the framework of algebraic models was undertaken. However, there still remain levels and decay properties which do not fit neatly into any model.

Accordingly, the two nuclei ^{187}Os and ^{189}Os have been probed using the Coulomb excitation reaction in order to determine the applicability of a pseudospin scheme [7] in this region of nuclei. In ^{187}Os the bands built on the ground and first excited states ($J^\pi = 1/2^-$ and $3/2^-$, respectively) are very nearly degenerate (only 10 keV separates the two bandheads) and can be thought of as pseudospin partners. The application of the SU(3) pseudospin scheme to the case of rotating nuclei leads to interesting predictions [8] regarding the $E2$ transition rates between levels in rotational bands, and it is these predictions which will be compared with the measured $B(E2)$ values and with the values expected in the limit that K is a good quantum number. In this latter case there should be no collective $E2$ transitions between members of different bands. By contrast, the pseudospin scheme yields strengths for collective interband transitions and thus the measurement of such transitions will be important in determining the applicability of this scheme to these nuclei.

Although it is in ^{187}Os that the 1/2 and 3/2 bands are nearly degenerate, they are only separated by 36 keV in ^{189}Os. It is therefore of interest to follow the predictions of the pseudospin scheme to this neighboring nucleus to test the bounds of its applicability. In addition it is hoped that the experiment will help uncover the structure of the 216 keV $5/2^-$ level in ^{189}Os. This state has been the subject of much discussion [2] as, until recently, it was thought to be the bandhead of the $7/2^-$ [503] Nilsson state [6]. Angular correlation and conversion electron measurements [2] have con-

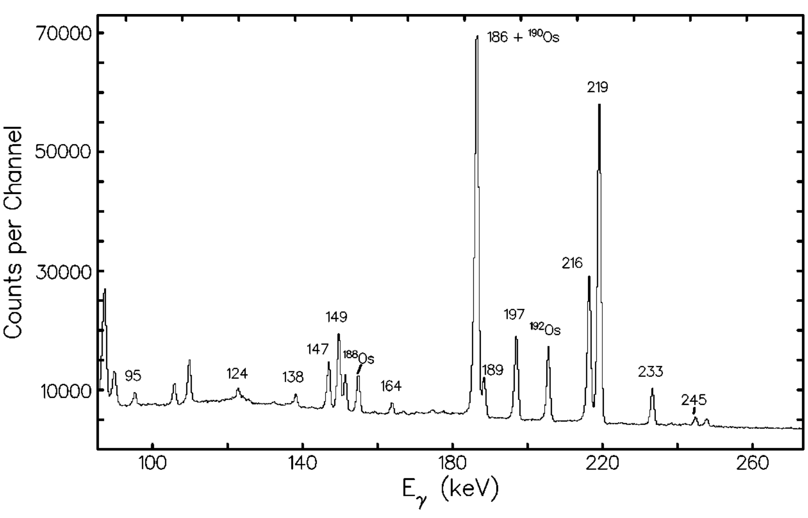

FIG. 1. γ-ray spectrum taken during the Coulomb excitation of ^{189}Os with a beam of 15 MeV α particles.

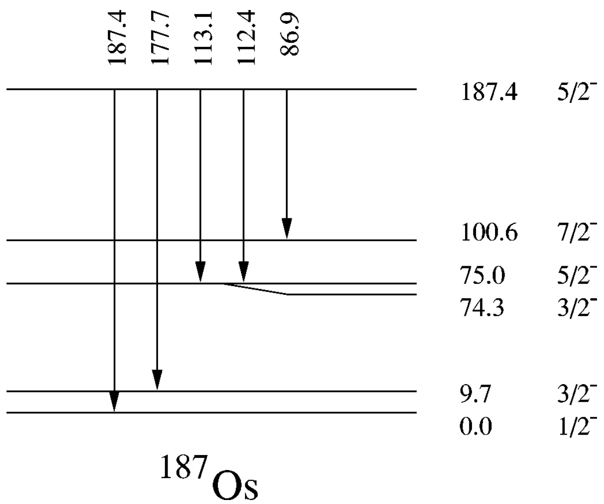

FIG. 2. Partial level scheme for ^{187}Os showing the levels populated by Coulomb excitation using a beam of 8 MeV α particles.

firmed it as a $5/2^-$ state but its structure is by no means clear. It is hoped that by measuring low-lying $B(E2)$ values this conundrum may be unraveled.

II. EXPERIMENTAL DETAILS

The experiments were done using the tandem Van de Graaff accelerator of the University of Cologne to produce α beams which bombarded thick ($\sim$20 mg cm^{-2}) targets enriched to 46.99% in ^{187}Os and 81.14% in ^{189}Os, respectively. The targets were made of powder pressed into pellets and placed inside packets of thin nickel (^{187}Os) or bismuth (^{189}Os). The experiment on ^{189}Os used a 15 MeV α-beam, whereas for ^{187}Os the beam energy was reduced to 8 MeV. The energy loss in the target was $\sim$4.2 MeV for ^{187}Os and $\sim$2.8 MeV for ^{189}Os. γ rays were detected in two large volume Germanium detectors placed at angles of 125° and 235° to the beam direction. A third, monitor, detector was placed at 30°. Figure 1 shows a typical γ-ray spectrum measured during the ^{189}Os experiment and Figs. 2 and 3 show the levels which were populated in the Coulomb excitation of ^{187}Os and ^{189}Os, respectively, along with the associated γ-ray decay. Since most of the Coulomb excitation took place at the front of the target, γ-ray energy and efficiency calibrations were obtained using a ^{226}Ra source of known activity placed on the front face of the target in order to account for attenuation in the target.

The thick target yields were obtained by integrating the yields calculated using the standard computer code [9] over the relevant energy region. Stopping powers taken from Ref. [10] were used in this calculation. Multiple excitations made no significant contribution in this study. $B(E2)$ strengths from the ground state were normalized to the observed intensities of the $2_1^+ \rightarrow 0_g^+$ transitions in neighboring ^{188}Os and ^{192}Os, using the known isotopic abundances of the target and the previously measured $B(E2)$ values of 2.51(7) and 2.04(2) e^2b^2 respectively [11,12]. [^{190}Os was not used in this comparison because the energy of the $2_1^+ \rightarrow 0_g^+$ (186 keV) overlaps with that of known transitions in ^{187}Os and ^{189}Os.] A number of additional $B(E2)$ values connecting excited states were obtained by using γ-ray branching ratios and measured δ values and internal conversion coefficients [2,13,14]. Table I lists the results of the measurements for ^{187}Os with those for ^{189}Os being listed in Table II.

A. ^{187}Os

The $B(E2)$ values measured in this experiment on ^{187}Os involve decays from the 187 keV $5/2^-$ state. This is the maximum spin value which can be populated by a single $E2$ excitation from the $1/2^-$ ground state. The introduction to this section already mentioned that, due to the isotopic admixtures present in the target, the 187 keV γ-ray contains contaminants from ^{190}Os and ^{189}Os. Therefore, in order to extract a $B(E2)$ value for this transition, its γ-ray intensity was calculated from branching ratios given in [13]. Internal conversion coefficients and mixing ratios were also taken from this reference.

B. ^{189}Os

The $B(E2)$ values measured for ^{189}Os are in good agreement with those previously published [14] except for those involving decays from the 95 keV level. The $B(E2)$ value

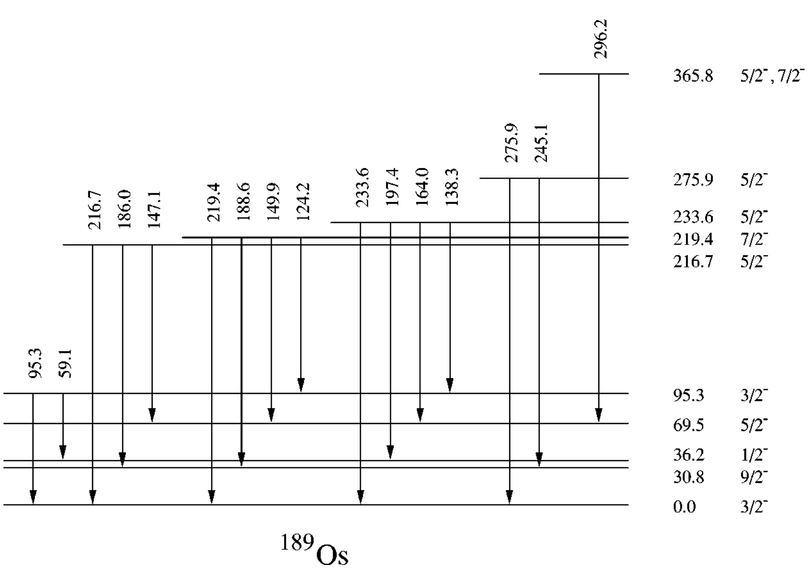

FIG. 3. Partial level scheme for ^{189}Os showing the levels populated by Coulomb excitation using a beam of 15 MeV α particles.

TABLE I. $B(E2)$ values determined for ^{187}Os.

E_i (keV)	J_i^π	E_f (keV)	J_f^π	E_γ (keV)	$B(E2)$ (e^2b^2)	$B(E2)$ prev (e^2b^2) [13]
187	$5/2^-$	0	$1/2^-$	187	0.446 (33)	0.464 (102)
		10	$3/2^-$	178	0.183 (29)	0.197 (57)
		74	$3/2^-$	113	0.441 (58)	0.483 (121)
		75	$5/2^-$	112	0.129 (17)	0.133 (19)
		101	$7/2^-$	87	1.449 (163)[a]	

[a]Assuming 87 keV transition is pure $E2$.

measured for the 95 keV transition from the 95 keV level to the ground state is a factor of $\sim$2 greater than the value quoted in Nuclear Data Sheets [14]. However, it is in agreement with the value of 0.17 e^2b^2 measured by Morgen *et al.* [4], using the (d,d') reaction and the value of 0.20 e^2b^2 measured by McGowan *et al.* [15] in a Coulomb excitation measurement. In the present measurement, the 59 keV γ-ray between the 95 keV and ground states was not observed but its intensity has been calculated by using the ratio of intensities of the 95 and 59 keV γ rays measured in a recent (n,γ) experiment [2]. Using this value for the γ-ray intensity and known δ values and internal conversion coefficients [14], the $B(E2)$ value quoted in Table II has been calculated.

The decay of the 216 keV level includes a 186 keV transition to the $9/2^-$ level at 30 keV. This transition has been observed in the decay of ^{179}Re [16,17] and of ^{179}Ir [18] but is contaminated in this experiment and in the (n,γ) reaction [2,6] by the $2_1^+ \rightarrow 0_g^+$ transition in ^{190}Os. The value of the gamma-ray intensity for this transition has therefore been taken from Nuclear Data Sheets [14] and is in agreement with values given in [16–18].

III. DISCUSSION

A. ^{187}Os

As stated in the Introduction, the low-lying $1/2^-$ and $3/2^-$ states in ^{187}Os are nearly degenerate and can therefore be considered as one pseudospin band consisting of a spin 1/2 part (labeled pseudospin) coupled to angular momenta values of $L=1,2,3,4\ldots$ (labeled total pseudo-orbital angular momentum). Figure 2 of Ref. [8] illustrates how the two bands can be thought of as stemming from one band of integer spin with the two levels arising from adding or subtracting the pseudospin of 1/2. This has a far reaching consequence because the two bands now stem from one underlying band and hence have a common intrinsic structure so that transitions between any states can now be thought of as in-band. For example, in the case of ^{187}Os, the transition between the $5/2^-$ state at 187 keV and the $5/2^-$ state at 75 keV is predicted to be strong in the pseudospin scheme, whereas in the ''good-K'' scheme it corresponds to a transition between states with different K values and hence is of single-particle strength. Predictions for the strength of individual transition in the pseudo-SU(3) scheme (taken from Ref. [8]) are given in Table III and compared with the measured $B(E2)$ values. Also listed are the predicted strengths of transitions in the ''good-K'' scheme where the strengths of in-band transitions have been calculated using the Alaga rules [19]. The first thing to note is the existence of quite strong transitions between states with different K values and in the good-K scheme these transitions should be of single-particle strength. In the case of decays from the $5/2^-$ level, the measured values agree well with the

TABLE II. $B(E2)$ values determined for ^{189}Os.

E_i (keV)	J_i^π	E_f (keV)	J_f^π	E_γ (keV)	$B(E2)$ (e^2b^2)	$B(E2)$ prev (e^2b^2) [14]
95	$3/2^-$	0	$3/2^-$	95	0.200 (18)	0.084 (26)
		36	$1/2^-$	59	0.564 (126)	0.168 (103)
216	$5/2^-$	0	$3/2^-$	216	0.195 (8)	$\geqslant$0.161
		30	$9/2^-$	186	0.170 (13)	$\geqslant$0.052
		69	$5/2^-$	147	0.142 (40)	$\geqslant$0.064
219	$7/2^-$	0	$3/2^-$	219	0.263 (10)	0.329 (58)
		30	$9/2^-$	189	0.044 (6)	$\leqslant$0.077
		69	$5/2^-$	149	0.229 (36)	0.374 (64)
		95	$3/2^-$	124	0.042 (10)	0.036 (7)
233	$5/2^-$	0	$3/2^-$	233	0.074 (3)	0.045 (13)
		36	$1/2^-$	197	0.158 (18)	0.174 (84)
		69	$5/2^-$	164	0.049 (20)	0.051 (39)
		95	$3/2^-$	138	0.112 (26)	0.097 (58)
275	$5/2^-$	0	$3/2^-$	275	0.011 (2)	0.014 (4)
		30	$9/2^-$	245	0.315 (66)	0.374 (77)
365	$5/2^-$	0	$3/2^-$	365	0.012 (1)[a]	0.015[a]
	$7/2^-$	0	$3/2^-$	365	0.009 (1)[b]	0.012[b]

[a]If 365 is 5/2 level.

[b]If 365 is 7/2 level.

TABLE III. Relative $B(E2)$ values in ^{187}Os. The absolute values are given in Table I.

J_i^π K_i^π	$J_f^\pi K_f^\pi$	E_γ (keV)	expt.	pseudo-SU(3)	good-K[a]
$5/2^- 1/2^-$	$1/2^- 1/2^-$	187	100 (7)	100	100
	$3/2^- 1/2^-$	113	99 (13)	86	29
	$3/2^- 3/2^-$	178	41 (6)	29	0
	$5/2^- 3/2^-$	112	29 (4)	21	0

[a]Calculated assuming pure-K values and ignoring single-particle contributions. The quadrupole moment is assumed to be constant and the same for both bands.

predictions of the pseudospin scheme. This implies that the pseudospin scheme automatically calculates the correct amount of mixing between the two bands, which is spin dependent. It would therefore be of interest to be able to measure $E2$ transition rates higher up the bands.

B. ^{189}Os

The $B(E2)$ values measured in the Coulomb excitation of ^{189}Os are listed in Table II and include values for transitions between states in nominal $K=1/2$ (36, 95, 233, and possibly 365 keV states) and $K=3/2$ (0, 69, and 219 keV states) bands. Other levels which are populated strongly from the ground state are the $5/2^-$ states at 216 and at 275 keV.

1. Interband/intraband transitions

Figure 4 shows the $B(E2)$ values which have been measured depopulating levels in the $1/2^-$ and $3/2^-$ bands in ^{189}Os discussed above. Although the strongest transitions observed are indeed in-band transitions, sizable interband transitions are also seen. This implies that there is some mixing between the bands and indeed previous authors, who tried to interpret the low-lying level structure of ^{189}Os [6] in terms of the Nilsson model, did comment on the need to include a strong Coriolis interaction in their calculations. Table IV lists the relative $B(E2)$ values for states in the $K=1/2$ and $K=3/2$ bands along with predictions from the ''good-K'' and pseudo-SU(3) schemes, the former calculated

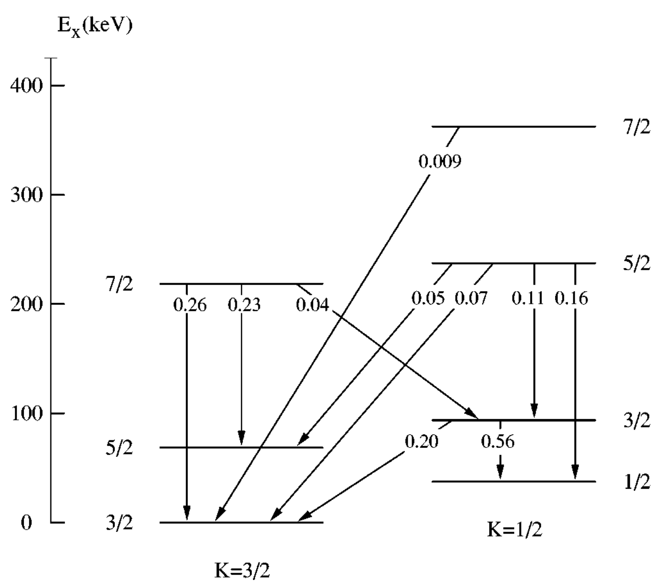

FIG. 4. Measured $B(E2)$ values in ^{189}Os and the associated band structure.

assuming that the quadrupole moment of each band is constant as a function of spin. The values have been normalized to the 197 keV transition between the $J^\pi,K^\pi=5/2^-,1/2^-$ and $1/2^-,1/2^-$ states and have been grouped according to the level from which they originate. While neither model is able to predict the relative strengths of transitions from different states, the pseudo-SU(3) model does appear to have more success in predicting the relative strengths of transitions from a given state. For example, although the 219 keV transition is observed to be slightly larger than predicted relative to the 197 keV transition, its measured strength relative to that of the 149 keV transition from the same level, is in better agreement with the pseudo-SU(3) predictions than the ''good-K'' values. In addition, the observed decays from the $J^\pi,K^\pi=5/2^-,1/2^-$ level at 233 keV appear to follow the pattern expected in the pseudo-SU(3) scheme rather than that expected in the ''good-K'' scheme. This indicates that the degree of mixing that exists between the two-bands is reasonably well approximated in the pseudo-SU(3) scheme.

In order to examine exactly how much the two bands are mixed, a two state mixing calculation has been done which uses the empirical $B(E2)$ values to calculate mixing amplitudes which were allowed to vary as a function of spin. This is illustrated in Fig. 5 where the $J=5/2$ level is parametrized as a linear combination of $K=1/2$ and $K=3/2$ states with the $J=3/2$ state being a different combination of $K=1/2$ and $K=3/2$ states. $E2$ transition rates involving bands of good K values are governed by the Clebsch-Gordan coefficients, therefore, ignoring single particle contributions, the $B(E2)$ value between the $J=5/2$, $K=1/2$ state (at 233 keV) and the $J=3/2$, $K=1/2$ state (at 95 keV) can be written as

$$B(E2)=\frac{5Q^2}{16\pi}[ac\langle 5/2\ 1/2\ 2\ 0|3/2\ 1/2\rangle + bd\langle 5/2\ 3/2\ 2\ 0|3/2\ 3/2\rangle]^2,$$

where

$$\langle 5/2\ 1/2\ 2\ 0|3/2\ 1/2\ \rangle$$

and

$$\langle 5/2\ 3/2\ 2\ 0|3/2\ 3/2\ \rangle$$

are standard Clebsch-Gordan coefficients. The value of the quadrupole moment Q, is assumed to be the same for both bands and has been calculated from the transition between the 233 keV state and the $J=1/2$ state at 36 keV state (assumed to be pure $K=1/2$). Similarly, the transition between

TABLE IV. Relative $B(E2)$ values in ^{189}Os, normalized to the 197 keV transition between the $J^\pi,K^\pi=5/2^-,1/2^-$ and $1/2^-,1/2^-$ states. The absolute values are given in Table II.

$J_i^\pi K_i^\pi$	$J_f^\pi K_f^\pi$	E_γ (keV)	expt	pseudo-SU(3)	good-K[a]
$3/2^- 1/2^-$	$1/2^- 1/2^-$	59	357 (79)	113	100
	$3/2^- 3/2^-$	95	127 (11)	113	0
$7/2^- 3/2^-$	$3/2^- 3/2^-$	219	166 (6)	129	71
	$5/2^- 3/2^-$	149	145 (23)	96	107
	$3/2^- 1/2^-$	124	27 (6)	11	0
$5/2^- 1/2^-$	$1/2^- 1/2^-$	197	100 (11)	100	100
	$3/2^- 1/2^-$	138	71 (16)	86	29
	$3/2^- 3/2^-$	233	47 (2)	29	0
	$5/2^- 3/2^-$	164	31 (13)	21	0
$7/2^- 1/2^-$[b]	$3/2^- 3/2^-$	365	6 (1)	0	0

[a]Calculated assuming pure-K values and ignoring single-particle contributions. The quadrupole moment is assumed to be constant and the same for both bands.
[b]Assumes 365 is 7/2 level.

the $J=5/2$, $K=1/2$ state (at 233 keV) and the $J=3/2$, $K=3/2$ state (at 0 keV) can be written

$$B(E2)=\frac{5Q^2}{16\pi}[bc\langle 5/2\ 1/2\ 2\ 0|3/2\ 1/2\rangle - ad\langle 5/2\ 3/2\ 2\ 0|3/2\ 3/2\rangle]^2.$$

The measured $B(E2)$ values, given in Table II, for the decay of the 233 keV ($5/2^-$) level to the two $3/2^-$ states at 0 and 95 keV indicate that the $5/2^-$ states (at 69 and 233 keV) are strongly mixed ($c^2=0.65$ and $d^2=0.35$), whereas, for the $3/2^-$ states $a^2=0.87$ and $b^2=0.13$. It is interesting to note that the amount of mixing calculated, for the $J=3/2$ and 5/2 states, using this relatively simple approach is quite close to that inherent in the pseudo-SU(3) scheme discussed above which gives 75, 25 % mixing for the $3/2^-$ states and 67, 33 % mixing for the $5/2^-$ states [20].

2. The 216 and 275 keV $5/2^-$ states

The strong population $[B(E2;216\rightarrow 0)=0.20e^2b^2]$ of the 216 keV level is of particular interest as this level has been the subject of much speculation [2]. The relatively large $B(E2)$ value suggests that the 216 keV transition has a collective nature and yet this is inconsistent with the assignment [6] of a significant $l=3$ transfer strength to it. Moreover, this level decays strongly not only to the $3/2^-$ and $5/2^-$ members of the $3/2^-$ band but also to the $9/2^-$ single-particle level (see Table II). The origins of this level have been discussed extensively in Ref. [2] where it was suggested that the measured transfer strength [6] belonged to the neighboring 219 keV level which would then not be the $7/2^-$ member of the $3/2^-$ band. However, the results of the current measurement do not support this argument as the measured $B(E2)$ values for the 219 keV level point strongly to its assignment as the $7/2^-$ member of the $3/2^-$ band.

The $5/2^-$ level at 275 keV has already been identified [18,6] as being built on the $9/2^-$ [505] level at 30 keV. However, it has also been labeled as ''anomalous'' [6] by virtue of a combination of collective character and significant neutron transfer strength similar to that of the 216 keV level. Indeed, its other decay branches are to the 216 keV level and the $3/2^-$ band [14]. Thus it seems likely that these shared characteristics imply a common origin and stem from mixing involving low-lying collective excitations which arise from the known onset of γ softness in this region.

IV. CONCLUSION

$B(E2)$ values have been measured for low-lying states in ^{187}Os and ^{189}Os and have been compared with values predicted using a pseudospin coupling scheme and a ''good-K'' approximation. In both nuclei, sizeable interband transitions were observed which implies mixing between states with different K values. The magnitude of the interband transitions are in overall good agreement with those predicted by the pseudo-SU(3) scheme. In the case of ^{189}Os, the empirical values have been used to extract mixing amplitudes in a

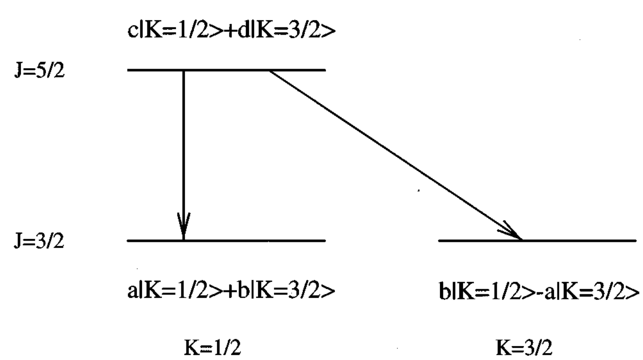

FIG. 5. The parametrization of levels in the band-mixing calculation.

two-band-mixing calculation. These amplitudes show the same spin dependence as those inherent in the pseudo-SU(3) scheme but the magnitudes are, not suprisingly, slightly different. Nevertheless, the results indicate that, even though the two bands in ^{189}Os are by no means degenerate, the pseudo-SU(3) scheme still has a degree of applicability to this nucleus.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. A. Dewald for technical assistance during the experiment and for preparing the target. The Nuffield foundation are thanked for providing A.M.B. with a grant for newly appointed science lecturers. C.T. would like to acknowledge the receipt of EPSRC support.

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