Identification of ^{109}Mo and possible octupole correlations in ^{107,109}Mo

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Ten new transitions in ^{107}Mo have been observed and levels in ^{109}Mo are identified for the first time in a γ-γ-γ coincidence study from the spontaneous fission of ^{252}Cf with 72 Compton suppressed Ge detectors in Gammasphere. Two sets of bands, each set intertwined by $E1$ transitions are observed in ^{107}Mo and one such set in ^{109}Mo. The observed level schemes are interpreted in terms of possible octupole deformation originating from the strong interaction of the $h_{11/2}$ and $d_{5/2}$ neutron shells. [S0556-2813(97)04009-0]

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I. INTRODUCTION

Static octupole shapes have been discovered in nuclei with $N=88$–90 and $Z=56$–58 regions associated with the $\nu f_{7/2}$-$\nu i_{13/2}$ and the $\pi d_{5/2}$-$\pi h_{11/2}$ orbitals, respectively [1–4]. Already it was known that static octupole deformation may be induced in nuclei where the Fermi level lies between single particle orbitals of the type $|N,L,j\rangle$ and $|N+1,L+3,j+3\rangle$ (e.g., $p_{3/2}-g_{9/2}$, $d_{5/2}-h_{11/2}$, $f_{7/2}-i_{13/2}$, etc.), because such orbitals couple strongly through the octupole potential term Y_{30} [5,6]. Calculations which include octupole and quadrupole deformation indicate that octupole effects (enhanced $E1$ crossing transitions between bands) may be observed in nuclei with Z and N around (34), 56, 90, 134. It was assumed that only proton or only neutron octupole coupling was not sufficiently strong to produce observable effects. It was thought that octupole coupling for both protons and neutrons in a nucleus was needed to give sufficient enhancement to produce observable octupole effects. The occurence of stable octupole deformation in $N=64$–66 nuclei has been predicted by Cottle [7,8].

Evidence for static octupole deformation has been reported in Ba [1–3], Ce [4], La [9], and Sm [10] nuclei associated with the proton and neutron orbitals noted above. In the deformed single particle shell model, two neutron orbitals $\nu d_{5/2}-\nu h_{11/2}$, lie near the Fermi surface for $N=64$–67. In the odd-A nuclei the situation is more complex. It has been early pointed out in the papers by Nazarewicz [11] and Chasman [12,13] that octupole shapes might be present in odd-mass nuclei and be absent in the neighboring doubly even systems and, secondly, octupole-deformed and reflection-symmetric shapes might occur in the same odd-A nucleus, depending on the properties of a single particle orbital. In this paper, we would like to point out the possibility that under certain conditions, only proton or only neutron octupole coupling may be sufficiently strong to observe the effects of an octupole shape. We suggest that this may occur if the Fermi level lies (1) not only between orbitals such as $p_{3/2}-g_{9/2}$, $d_{5/2}-h_{11/2}$, $f_{7/2}-i_{13/2}$, etc., to drive the octupole coupling but also (2) the closest Nilsson levels near the Fermi level have $\Omega_1=\Omega_2$, for example, the $5/2^+$ [413] and $5/2^-$ [532] orbitals. In this case, the overlap between the $d_{5/2}$ and $h_{11/2}$ orbitals may be maximal and thus yield enhanced octupole coupling in neutron rich Mo and Tc nuclei.

The Mo nuclei with $N=65$–67 are the best possible candidates for the observation of parity doublets related to static octupole deformation. The Ba and Mo nuclei produced in the spontaneous fission (SF) of ^{252}Cf are partners and the Ba nuclei have static octupole deformed shapes [1–3]. According to previous work [14], the ^{107}Mo level scheme is very different from those of the other lighter odd-A Mo nuclei, and the structure of the low-lying levels of ^{107}Mo is not obvious. In the present work, we have investigated the band structure of ^{107}Mo in search for evidence of octupole deformation. We have identified in ^{107}Mo ten new transitions and new band structures which are shown to be connected by the intertwined $E1$ transitions. These new band structures are interpreted as the parity doublets related to static octupole

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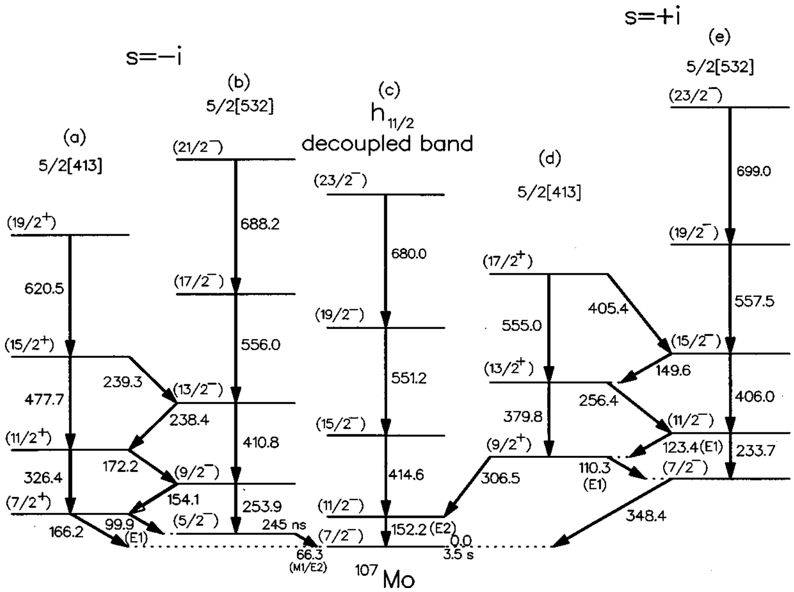

FIG. 1. Level scheme of ^{107}Mo.

deformation. Also, we have identified for the first time nine γ-ray transitions in ^{109}Mo. The level scheme of ^{109}Mo is similar to that of ^{107}Mo but with only one intertwined band observed. From these data, we suggest that the ^{107,109}Mo nuclei have static octupole deformations. This is the first evidence for octupole deformation related to only one type of nucleons and in particular to the $\nu d_{5/2} - \nu h_{11/2}$ orbitals in the $N = 65$–67 region.

II. EXPERIMENTS

A new level scheme of ^{107}Mo, and identification of levels in ^{109}Mo were extracted from the analysis of γ-ray spectra produced in the spontaneous fission of ^{252}Cf. A 25 μCi ^{252}Cf source was sandwiched between two Ni foils of thickness 0.5 mil and then sandwiched between 2 mil thick Al foils and was placed at the center of Gammasphere with 72 Compton suppressed Ge detectors at Lawrence Berkeley National Laboratory. A total of 9.8×10^9 triple or higher fold coincidence events were recorded. The Gammasphere was calibrated with ^{133}Ba, ^{137}Cs, ^{152}Eu, ^{56}Co, and ^{57}Co sources. A γ-γ-γ cube was built using the RADWARE software [15]. The complex γ-ray spectra obtained in SF were analyzed by the triple γ coincidence method. For a given fission fragment there can be many partner isotopes because 0 to ~ 10 neutrons can be emitted from the primary fragments following scission. The γ rays emitted by two partners during deexcitation will be in coincidence with each other. If the transitions in one of the partner nuclei are known, one can assign the γ rays belonging to the other partner nucleus uniquely, by using the triple coincidence technique.

If we set a double gate on the well known transitions in ^{107}Mo, we obtain the yield ratios for its Ba partners. If we get the same yield ratios by setting double gates on unassigned γ rays, then the γ rays in the double gates should belong to the ^{107}Mo nucleus. Wahl [16] gives the total yield of each Ba isotope. The variation of the yield ratios (γ-transitions intensities) of each Ba partner nucleus was determined in our recent work [17]. Many double gated coincidence spectra were analyzed to assign uniquely the new transitions to ^{107}Mo. The γ rays belonging to ^{109}Mo also were identified by comparing the yield ratios of Ba partners. Details are discussed in the results section.

Total internal conversion coefficients (α_T) for several low-energy transitions were determined from the intensity balance in and out of a level. For example the total internal conversion coefficient of the 152.2-keV transition (see Fig. 1) was determined by comparing the relative intensities of the 306.5- and 152.2-keV transitions in a coincidence spectrum obtained by gating on the 123.4-keV γ ray in ^{107}Mo and the 359.3-keV γ ray in ^{142}Ba. The difference in the relative intensities of the 306.5- and 152.2-keV γ rays should be equal to conversion electron intensity for the 152.2-keV transition. The theoretical value [$\alpha_T(E1) = 0.00526$] of the conversion coefficient for the 306.5 keV transition is negligible because of its higher energy.

Alternatively, one can obtain α_T by double gating on two transitions in the same nucleus. For example, by double gating on 110.3- and 149.6-keV transitions, the α_T of the 123.4-keV transition can be extracted, by measuring the difference in relative intensities of the 256.4- and 123.4-keV transitions.

III. RESULTS

A. ^{107}Mo nucleus

The new level scheme of ^{107}Mo is shown in Fig. 1. The bands labeled (c), (d), and (e) in Fig. 1, are already identified by Hotchkis *et al.* [14]. They also assigned transitions 477.7-, 326.4-, 556.0-, 410.8-, 253.9-, and 66.3-keV to ^{107}Mo. We have extended the bands (c) and (e) to higher spins. The nuclei $^{140-144}$Ba are some of the partners of ^{107}Mo with 5 to 1 neutrons emitted, respectively. In Fig. 2(a), the coincidence spectrum obtained by double gating on the new 166.2-keV and already known 326.4-keV transitions is shown. In this spectrum the observed yields of $^{140-144}$Ba nuclei are similar to the yields obtained from the intensity analysis of transitions of Ba partners obtained by double gating on two previously known 110.3- and 348.4-keV transitions in ^{107}Mo and to the yield from our more recently completed result [17]. For example, the peak intensity ratio of $I_{342.9}(^{143}\mathrm{Ba})/I_{359.3}(^{142}\mathrm{Ba}) = 2n$ channel/3n channel is 0.47

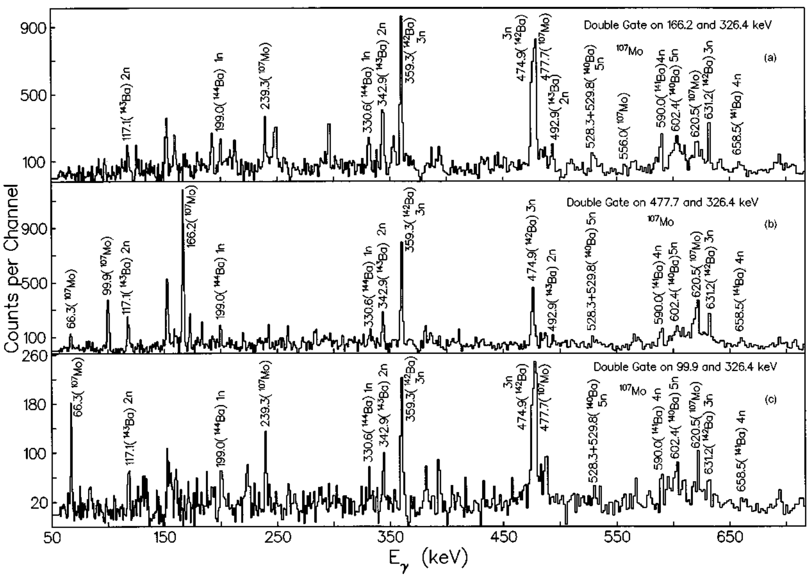

FIG. 2. (a) Coincidence spectrum obtained by double gating on the 166.0 and 326.2 keV transitions in ^{107}Mo. (b) Coincidence spectrum obtained by double gating on the 477.7 and 326.4 keV transitions in ^{107}Mo. (c) Coincidence spectrum obtained by double gating on the 99.9 and 326.4 keV transitions in ^{107}Mo. In these three spectra, the transitions belonging to the partner Ba nuclei are indicated.

[see Fig. 3(a)]. The peak of the Ba/Mo neutron emission is at $4n$ [17]. In the coincidence spectra [Fig. 2(a) and 2(c)] the intensity ratios for the same peaks are 0.49 and 0.43, respectively. Hence the 99.9- and 166.2-keV transitions belong to ^{107}Mo. The 556.0-keV peak which appears to be weak in Fig. 2(a), can be readily observed in the 253.9- and 410.8-keV double gate. The 688.2-keV transition can be also seen in this gate, and even more strongly, in the 253.9-and 556.0-keV or 410.8-and 556.0-keV gates. In Fig. 2(b), the coincidence spectrum obtained by double gating on the known 326.4- and 477.7-keV transitions is shown. In this spectrum one clearly sees the new 166.2-, and 99.9-keV γ rays. In Fig. 2(c) the coincidence spectrum obtained by double gating on the 99.9- and 326.4-keV transitions is shown. In this spectrum one can see clearly the 66.3- and 239.3-keV transitions. By analyzing several coincidence spectra, ten new transitions of energies 99.9-, 154.1-, 166.2-, 172.2-, 239.3-, 238.4-, 620.5-, 680.0-, 688.2-, and 699.0-keV were placed in the level scheme of ^{107}Mo as shown in Fig. 1.

Previously Hotchkis *et al.* [14] did not assign any spins to the levels of ^{107}Mo. The measured total internal conversion coefficients (α_T) for some low-energy transitions and systematics were used to propose spins and parities to the levels of ^{107}Mo. An excited decoupled $\nu h_{11/2}$ band has been reported in ^{103} Mo [14] with a bandhead tentatively assigned spin and parity of $7/2^-$. The transition that feeds this level has an $E2$ character. The transition energies in band (c) in Fig. 1 are very similar to those of the decoupled band in ^{103}Mo. The α_T of the 152.2 keV transition [see Table I] shows that it has an $E2$ character, such as the band in ^{103}Mo. Thus a spin and parity of $7/2^-$ is tentatively assigned to the ground level. The next band members are assigned $11/2^-$, $15/2^-$, $19/2^-$, and $23/2^-$ by assuming that the next three transitions are also $E2$. Also, the transition energies in band (c) Fig. 1 are very similar to those of the ground rotational band in ^{106}Mo. This implies that core nucleus of this decoupled band in ^{107}Mo is ^{106}Mo.

The α_T of the 123.4-keV transition was measured by double gating on 149.6- and 110.3-keV transitions. In this gate the difference in the relative intensities of the 256.4- and 123.4-keV transitions is equal to the electron intensity. The conversion electron intensity for the 110.3-keV transition

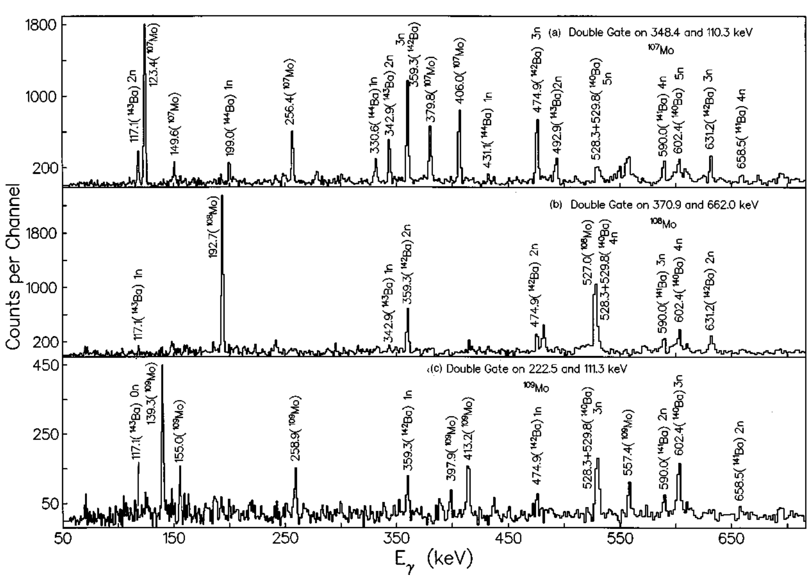

FIG. 3. (a) Coincidence spectrum obtained by double gating on the 348.4 and 110.3 keV transitions in ^{107}Mo. (b) Coincidence spectrum obtained by double gating on the 370.9 and 662.0 keV transitions in ^{108}Mo. (c) Coincidence spectrum obtained by double gating on the 222.5 and 111.3 keV transitions in ^{109}Mo. In these three spectra, the transitions belonging to the partner Ba nuclei are indicated. Note the $0n$ channel ^{143}Ba is not seen here as it is for the $2n$ channel in Fig. 3(a) as expected.

TABLE I. Values of internal conversion coefficients extracted for low energy transitions.

Nucleus	E_γ (keV)	Experimental α_{tot}	Theoretical α_{tot} $E1$	$M1$	$M2$	$E2$
^{107}Mo	99.9($E1$)	0.15(3)	0.13	0.26	2.65	1.20
	110.3($E1$)	0.06(2)	0.09	0.19	1.84	0.84
	123.4($E1$)	0.03(4)	0.07	0.14	1.23	0.56
	152.2($E2$)	0.32(8)	0.04	0.08	0.59	0.27
^{109}Mo	139.3($E1$)	0.04(3)	0.05	0.10	0.79	0.55

was obtained by double gating on 348.4-keV transition in ^{107}Mo and 359.5-keV transition in ^{142}Ba. The difference in the relative intensities of $I_{123.4}+I_{379.8}$ and $I_{123.4}$ transitions is equal to the conversion electron intensity of 110.3-keV transition. The α_T's given in Table I establish that these two γ rays have $E1$ character.

The K-conversion coefficient of $1.8^{+0.5}_{-1.0}$ [14] for the 66.3-keV transition indicates that it has a mixed $M1/E2$ character. The measured half life of 245(15) ns for the 66.3-keV level [18] is consistent with $M1/E2$ character. So the parity of the 66.3-keV level should be the same as that of the ground state. The α_T of the 99.9-keV transition was measured from the intensity balance in and out of the 166.2-keV level in a spectrum obtained by double gating on the 66.3-keV transition and 410.8-keV transition. This result indicates that the 99.9-keV transition has $E1$ character as shown in Table I. The $M1/E2$ character of the 66.3-keV transition establishes the negative parity of the 66.3-keV level. The γ-ray energies in this band are very similar to the transitions in $5/2^-$ [532] band in ^{105}Mo and ^{101}Zr. The band (b) may be originating from this configuration. Thus, we tentatively assigned the spin and parity of the 66.3-keV level as $5/2^-$. Since the 99.9-keV transition is $E1$, there should be a change of parity between bands (a) and (b). The higher members of these bands are assumed to be connected via $E2$ transitions. The γ transitions in the band built on the $7/2^-$ level in ^{105}Mo and ^{101}Zr have energies similar to those in band (e) in ^{107}Mo. Thus, the 348.4-keV level is assigned $7/2^-$. The 458.7 keV level should have spin and parity of $9/2^+$ because the 110.3 keV transition is $E1$. Based on these systematics, tentative spin and parities are assigned to the levels in ^{107}Mo. In the present work, two sets of parity doublets are indicated.

B. ^{109}Mo nucleus

The new 222.5- and 111.3-keV transitions are assigned to ^{109}Mo on the basis of the following considerations. The coincidence spectrum [Fig. 3(c)] with a double gate on the 222.5- and 111.3-keV transitions assigned to ^{109}Mo shows the γ transitions of $^{143-140}$Ba partners. The 222.5- and 111.3-keV transitions cannot belong to ^{110}Mo since the 359.3-keV transition in ^{142}Ba is too strong to be the 0 neutron channel. Also, these transitions cannot belong to ^{108}Mo because the 602.4 keV transition of ^{140}Ba is too strong when this coincidence spectrum is compared with a coincidence spectrum [Fig. 3(b)] with the double gate on the known 370.9- and 662.0-keV transitions of ^{108}Mo. Based on this analysis, the 222.5- and 111.3-keV transitions are the first

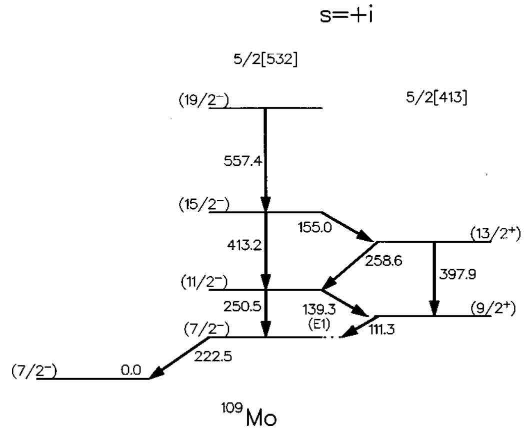

FIG. 4. Level scheme of ^{109}Mo.

transitions placed in the level scheme of ^{109}Mo. From Fig. 3(c), we identified new γ transitions of 139.3, 397.9, 258.6, 155.0, 413.2, and 557.4 keV in ^{109}Mo. The new level scheme of ^{109}Mo is shown in Fig. 4. The suggested spins and parities tentatively assigned to the levels in ^{109}Mo are based on similarities to ^{107}Mo, and on the $E1$ character of the 139.3-keV transition. The α_T of the 139.3-keV transition (see Table I) obtained by double gating on the 111.3- and 222.5-keV transitions [see Fig. 3(c)] indicates that the 139.3-keV transition has $E1$ character but the uncertainty overlaps with $M1$ assignment within two standard deviations (2σ).

IV. DISCUSSION

In a reflection asymmetric nuclear field, simplex quantum numbers are used to classify the parity doublet states. In ^{107}Mo, $s=+i$ can be assigned to the sequence $7/2^-$, $9/2^+$, $11/2^-$, $13/2^+$, $15/2^-$, $17/2^+$, $19/2^-$, $21/2^+$, $23/2^-$ and $s=-i$ to the sequence $5/2^-$, $7/2^+$, $9/2^-$, $11/2^+$, $13/2^-$, $15/2^+$, $17/2^-$. On the other hand, only one $s=+i$ band with states $7/2^-$, $9/2^+$, $11/2^-$, $13/2^+$, $15/2^-$, $17/2^+$, $19/2^-$, $21/2^+$, $23/2^-$ is indicated in ^{109}Mo. The energy splitting, $\delta E(I)$ of a band with octupole structure can be evaluated from the experimental level energies by using the relations

$$\delta E(I^+)=E(I^+)-\frac{(I+1)E(I-1)^- + IE(I+1)^-}{2I+1} \quad (1)$$

and

$$\delta E(I^-)=E(I^-)-\frac{(I+1)E(I-1)^+ + IE(I+1)^+}{2I+1}. \quad (2)$$

Figure 5 compares $\delta E(I)$ versus $(I-I_0)$ curves of ^{143}Ba and ^{107,109}Mo, where I_0 is the ground state spin. The superscripts $\pm$ indicate the parity of the levels. In the limit of stable octupole deformation, $\delta E(I)$ should be close to zero. As seen in Fig. 5, the parity doublet bands discovered in ^{107,109}Mo show fluctuations along the $\delta E(I)=0$ line similar to ^{143}Ba. This suggests that ^{107,109}Mo have a well defined static octupole shape similar to that observed in ^{143}Ba. Also the ratio of the rotational frequencies can be evaluated from the experimental level energies by using the relations

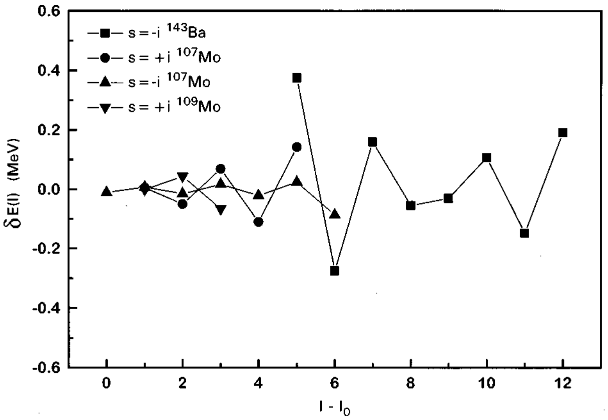

FIG. 5. Plot of $\delta E(I)$ vs $(I-I_0)$. See Eqs. (1) and (2) in the text. The error bars are of the size of the point.

$$R(I^+)=\frac{\omega^+(I)}{\omega^-(I)}=2\frac{E(I+1)^+-E(I-1)^+}{E(I+2)^- - E(I-2)^-} \tag{3}$$

and

$$R(I^-)=\frac{\omega^-(I)}{\omega^+(I)}=2\frac{E(I+1)^- - E(I-1)^-}{E(I+2)^+-E(I-2)^+}. \tag{4}$$

The variation of $R(I)$ as a function of $(I-I_0)$ for ^{107,109}Mo and ^{143}Ba is plotted in Fig. 6. At the limit of stable octupole deformation, the ratio between the rotational frequencies of the positive and negative parity bands should approach unity. In Fig. 6, one can see that these ratios fluctuate around unity. Thus these ratios likewise indicate that ^{107,109}Mo have well defined static octupole shapes. The nucleus with octupole bands decays through $E1$ and $E2$ transitions. The $B(E1)/B(E2)$ branching ratios are evaluated by the expression

$$\frac{B(E1)}{B(E2)}=0.711\frac{I_\gamma(E1)}{I_\gamma(E2)}\frac{E(E2)^5}{E(E1)^3}(10^{-6}\ \ \mathrm{fm}^{-2}), \tag{5}$$

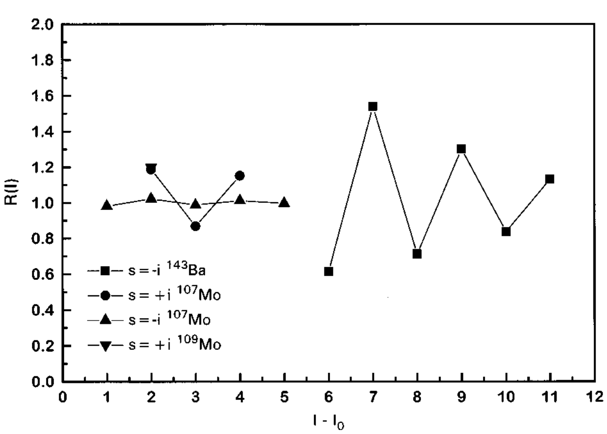

FIG. 6. Ratios $[R(I)]$ of the rotational frequencies vs $(I-I_0)$, where I is the spin of the level and I_0 is the spin of the ground state. See Eqs. (3) and (4) in the text. The error bars are of the size of the point.

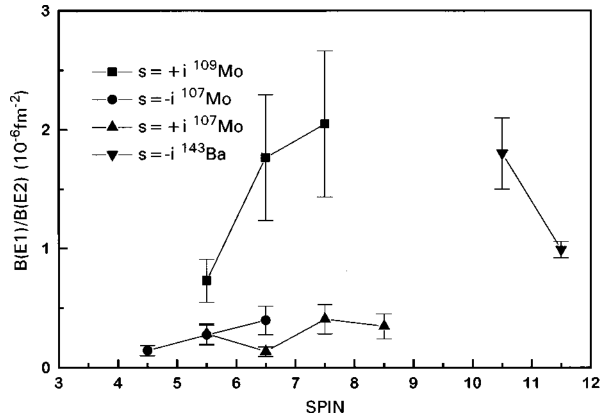

FIG. 7. $B(E1)/B(E2)$ branching ratios in ^{107,109}Mo and ^{143}Ba nuclei.

where the intensities and energies have been taken from the present work. As can be seen in Fig. 7 and Table II, the average $B(E1)/B(E2)$ values for ^{107}Mo are 0.27(8) 10^{-6} fm^{-2} for the $s=+i$ and 0.29(9) 10^{-6} fm^{-2} for the $s=-i$ band. Also the $B(E1)/B(E2)$ branching ratio values in the parity doublet bands of ^{107}Mo are similar to the $B(E1)/B(E2)$ branching ratios in the parity doublet bands of ^{151}Pm [19] which is formed by the octupole coupling of the proton 5/2[413] and proton 5/2[532] orbitals. The average $B(E1)/B(E2)$ value for ^{109}Mo is 1.5(4) 10^{-6} fm^{-2} for the $s=+i$ band, similar to the ratios in ^{143}Ba. The $B(E1)/B(E2)$ branching ratios in ^{107}Mo are an order of magnitude smaller than in ^{109}Mo and ^{143}Ba. This effect is similar to the situation in ^{145,147}La [14], where $B(E1)/B(E2)$ branching ratios in ^{145}La are an order of magnitude larger than in ^{147}La. Therefore it implies that the octupole correlations are stronger for $N=67$ than for $N=65$.

TABLE II. $B(E1)/B(E2)$ branching ratios in ^{107,109}Mo. Intensities are normalized to a value of 100.

Nucleus	E_γ (keV)	$I^\pi \to I^\pi$	I_γ	$B(E1)/B(E2)$ 10^{-6} fm^{-2}
^{107}Mo	154.1	$9/2^-$ $7/2^+$	70.9	0.15(4)
	253.9	$9/2^-$ $5/2^-$	100^+	
	172.2	$11/2^+$ $9/2^-$	53.4	0.28(8)
	326.4	$11/2^+$ $7/2^+$	100^+	
	239.3	$13/2^-$ $11/2^+$	65.6	0.4(1)
	410.8	$13/2^-$ $9/2^-$	100^+	
	123.4	$11/2^-$ $9/2^+$	109.8	0.29(9)
	233.7	$11/2^-$ $7/2^-$	100^+	
	256.4	$13/2^+$ $11/2^-$	41.0	0.14(4)
	379.8	$13/2^+$ $9/2^+$	100^+	
	149.6	$15/2^-$ $13/2^+$	17.4	0.4(1)
	406.0	$15/2^-$ $11/2^-$	100^+	
	405.4	$17/2^+$ $15/2^-$	61.9	0.35(1)
	555.0	$17/2^+$ $13/2^+$	100^+	
^{109}Mo	139.3	$11/2^-$ $9/2^+$	74.7	0.73(18)
	326.4	$11/2^-$ $7/2^-$	100^+	
	258.6	$13/2^+$ $11/2^-$	430.7	1.8(5)
	397.9	$13/2^+$ $9/2^+$	100^+	
	155.0	$15/2^-$ $13/2^+$	89.1	2.1(6)
	413.2	$15/2^-$ $11/2^-$	100^+	

V. SUMMARY AND CONCLUSION

Ten new transitions in ^{107}Mo have been observed and levels in ^{109}Mo are identified for the first time in a γ-γ-γ coincidence study of the spontaneous fission of ^{252}Cf. Spins and parities of levels in ^{107,109}Mo have been assigned on the basis of total internal conversion coefficients and the systematics of the level schemes of the neighboring Mo nuclei. Two sets of bands, each set intertwined by $E1$ transitions are observed in ^{107}Mo and one such set in ^{109}Mo. These data along with the $B(E1)/B(E2)$ ratios indicates the new region of octupole deformation. We propose that the origin of this new region of static octupole deformation is related to the presence and strong overlap of the $h_{11/2}5/2[532]$ and $d_{5/2}5/2[413]$ neutron orbitals near the Fermi surface for deformed nuclei with $N=64$–67. This is the first time such octupole deformation is reported based on only one pair of the nucleon orbitals. The $B(E1)/B(E2)$ branching ratios indicate that the octupole correlations are stronger in $N=67$ than in $N=65$.

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