Prompt γ-ray spectroscopy of the ^{104}Mo and ^{108}Mo fission fragments

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The level structures of the neutron-rich ^{104}Mo and ^{108}Mo nuclei have been investigated by observing prompt γ rays emitted in the spontaneous fission of ^{248}Cm with the EUROGAM spectrometer. Levels with spins up to $12\hbar$ have been observed and γ branching obtained. The data can be satisfactorily described when ^{104,108}Mo are considered as axially symmetric nuclei: in ^{104}Mo, rotational bands based on the ground state, the one-phonon and the two-phonon γ-vibrational states and a quasiparticle state have been observed, whereas in ^{108}Mo the information is limited to the yrast band and the one phonon γ band.

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I. INTRODUCTION

In a recent letter we reported the observation of a harmonic two phonon γ-vibrational state in the neutron-rich ^{106}Mo nucleus [1]. The level scheme revealed several rotational bands built on either the ground state, the one phonon γ-vibrational state, the two phonon γ-vibrational state, or quasiparticle states. The present paper is a report on the nuclear structure of the two neighboring even-even nuclei, ^{104}Mo and ^{108}Mo. Level schemes for the three neutron-rich Mo isotopes result from experimental studies of the spontaneous fission of a ^{248}Cm source using the multidetector array EUROGAM. Induced or spontaneous fission is indeed the only way at the present time for producing medium spin structures in neutron-rich nuclei and the use of a multifold γ-coincidence technique is necessary in order to obtain the sensitivity needed for γ rays of interest to be studied among all the prompt γ rays emitted in the fission process.

The level scheme of ^{104}Mo has previously been investigated through spectroscopy of the γ radiations following the β decay of ^{104}Nb [2]. The yrast structure has been deduced from a similar but less efficient experiment than the present one and yrast states with I^{π} up to 10^{+} and 8^{+} have been reported for ^{104}Mo and ^{108}Mo, respectively [3]. The characteristics of the level schemes of ^{104,106}Mo have been related to classical rotors or to rigid triaxial rotors [2,4]. Data from the present experiment were recently analyzed to study the deformation in the neighboring even-even Ru isotopes [5] and relative electromagnetic transition probabilities were found to be in good agreement with predictions of a rigid triaxial rotor model. Further analysis of the experimental data to examine structures and deformations in the neutron-rich Mo isotopes was undertaken and here we present the information obtained on ^{104}Mo and ^{108}Mo.

II. EXPERIMENT AND RESULTS

The decay schemes of ^{104}Mo and ^{108}Mo have been investigated by measuring the prompt γ rays emitted immediately after their formation in the spontaneous fission of ^{248}Cm. The ^{248}Cm source had a fission rate of roughly 6.3×10^{4} fissions/s and was made by embedding curium oxide in a KCl pellet. The fission fragments were stopped within 1 to 2 ps and thus most of the γ rays of interest in this study were emitted at rest and thus suffered no Doppler broadening. The γ rays were observed with the EUROGAM spectrometer which in its first phase was located at the Nuclear Structure Facility, Daresbury Laboratory. The EUROGAM array [6] used in this experiment consisted of 45 large volume germanium detectors of $\geqslant$70% relative efficiency, each detector being surrounded by bismuth germanate scintillators to reduce the Compton background. In order to improve the detection efficiency at low γ-ray energies, five low energy photon spectrometers were added to the array. We recorded events in which at least three unsuppressed Ge detectors fired. This gave mostly doubles and triples of Compton suppressed events on tape. The condition also considerably reduced the recording of events associated with delayed γ rays from β decay, due to their low γ-ray multiplicity, without affecting prompt γ-ray events very much.

The extension of the level schemes was achieved by using one-dimensional spectra of γ rays in coincidence with two or three additional γ rays. More precisely bidimensional matri-

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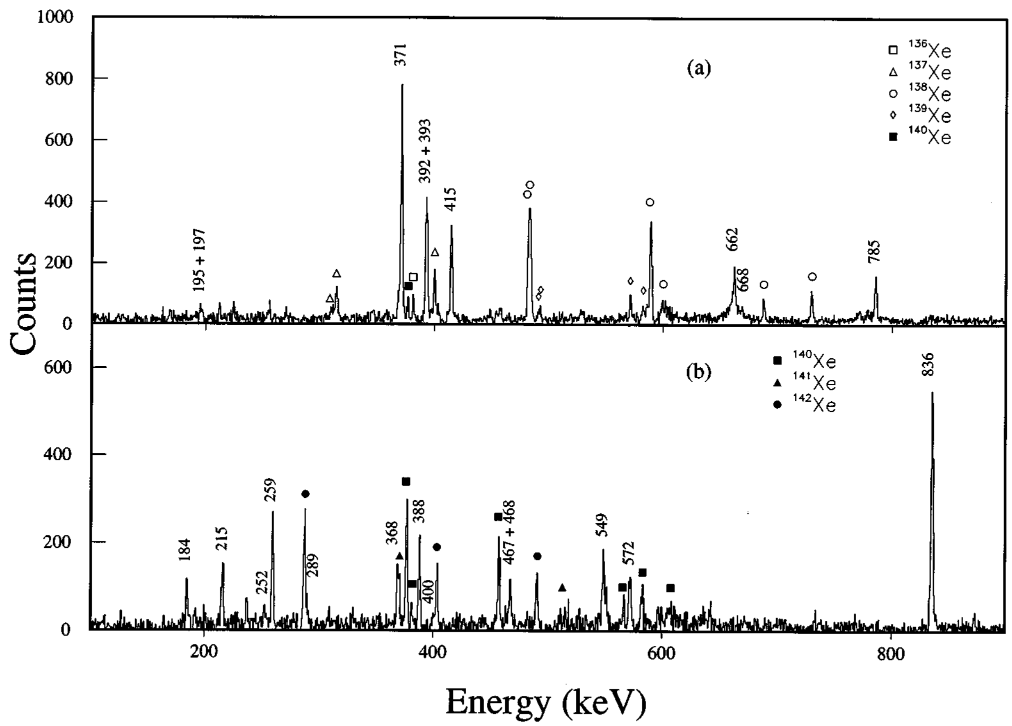

FIG. 1. Portions of selected γ-ray spectra obtained from triple γ coincidences. γ rays corresponding to complementary fragments are marked by symbols. (a) Ge spectrum in coincidence with a raw gate on the 192.7 keV γ transition and a background subtracted gate on the 529.5 keV γ transition in ^{108}Mo. The line at 376.6 keV corresponds to the $2^+ \rightarrow 0^+$ γ transition in ^{140}Xe and results from the spontaneous fission of ^{248}Cm with zero neutron emission. (b) Ge spectrum in coincidence with a raw gate on the 192.0 keV γ transition and a background subtracted gate on the 796.1 keV γ transition in ^{104}Mo.

ces were constructed with events fulfilling one or two energy requirements, i.e., events selected by one or two gates set on threefold or fourfold γ coincidences, respectively. One-dimensional spectra were then obtained by setting gates corresponding to specific γ peaks on an axis of a matrix and by subtracting the contribution due to the background. Examples of such spectra are shown in Figs. 1 and 2. Each Mo fragment in the spontaneous fission of ^{248}Cm is associated with a complementary Xe fragment, whose mass depends on the number of emitted neutrons. Therefore a γ spectrum obtained by setting gates on transitions in a Mo isotope displays also γ lines corresponding to several Xe isotopes, as it can be seen in Fig. 1.

Spin and parity assignments are based on previous work [2,3] and the observed decay paths of the levels. In addition assignments result also from the similarities of the two level schemes with the one of ^{106}Mo. For this nucleus, spins were attributed to states by analyzing data obtained in a similar experiment with EUROGAM phase 2 [1]. The increase in statistics, roughly an order of magnitude, permitted the assignment of multipolarities to transitions from ratios of double and triple angular correlation data. Examples of ratios

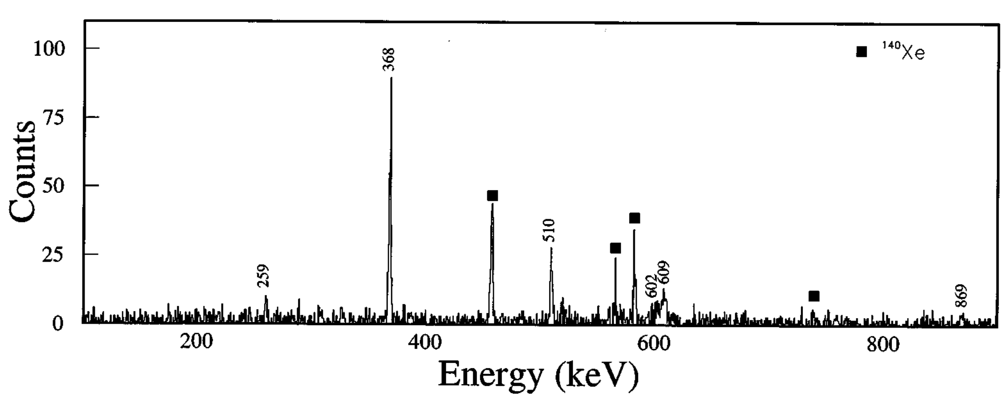

FIG. 2. Quadruple-coincidence data showing a Ge detector spectrum in coincidence with the raw gate on the $2_1^+ \rightarrow 0_1^+$ transitions in both ^{104}Mo and ^{140}Xe and the background subtracted gate on the $4_2^+ \rightarrow 4_1^+$ transition in ^{104}Mo. Transitions are labeled by their energies (in keV) for ^{104}Mo and by full squares for ^{140}Xe.

TABLE I. DCO ratios for triple and double angular correlations in the ^{106}Mo nucleus. The considered transitions are associated to stretched quadrupole transitions. Predictions [7,8] of DCO ratios for the EUROGAM 2 array for triple (double) angular correlations give the following values: 1.00 (0.89) for a stretched quadrupole transition and 1.20 (1.09) for a stretched dipole transition.

	DCO ratios			DCO ratios	
Transition	$\gamma\gamma\gamma$	$\gamma\gamma$	Transition	$\gamma\gamma\gamma$	$\gamma\gamma$
$4_1^+\rightarrow 2_1^+$		0.94(1)	$5_1^+\rightarrow 3_1^+$		0.93(3)
$6_1^+\rightarrow 4_1^+$	1.00(2)	0.94(1)	$6_2^+\rightarrow 4_2^+$		0.90(3)
$8_1^+\rightarrow 6_1^+$	0.99(3)		$6_2^+\rightarrow 4_1^+$	1.02(6)	0.94(2)
$3_1^+\rightarrow 2_1^+$	1.19(6)	1.07(2)	$7_1^+\rightarrow 6_1^+$	1.15(6)	
$5_1^+\rightarrow 4_1^+$	1.14(6)	1.05(1)	$5_2^+\rightarrow 4_2^+$	1.23(7)	1.00(1)

of angular correlations, also called DCO (directional correlations from oriented states) ratios, are given in Table I.

The level schemes of ^{104}Mo and ^{108}Mo obtained in the present work are shown in Figs. 3 and 4. All γ-transition energies have been determined with an accuracy of $\leqslant$ 0.2 keV, except for the 466.4 and 776.6 keV transitions in ^{108}Mo for which ΔE_γ=0.3 keV. The γ branching for ^{104}Mo and ^{108}Mo are reported in Table II, along with the hitherto unpublished branching ratios for ^{106}Mo.

Only one extra transition has been added to the yrast line in ^{104}Mo. The agreement between the present level scheme and the results of the β-decay study of ^{104}Nb is rather good for the eight excited states observed in both studies: three in the yrast band, four in the lowest side band and the levels at 1583 and 2061 keV. The tentative 1215 $\rightarrow$ 812 keV and 1583 $\rightarrow$ 1215 keV γ decays are confirmed in the present work which adds two more transitions between already known states, namely the 1028 $\rightarrow$ 560 keV and 1475 $\rightarrow$ 1028 keV decays. In the ^{108}Mo nucleus all transitions, except the γ cascade starting from the 8_1^+ state, have been observed for the first time.

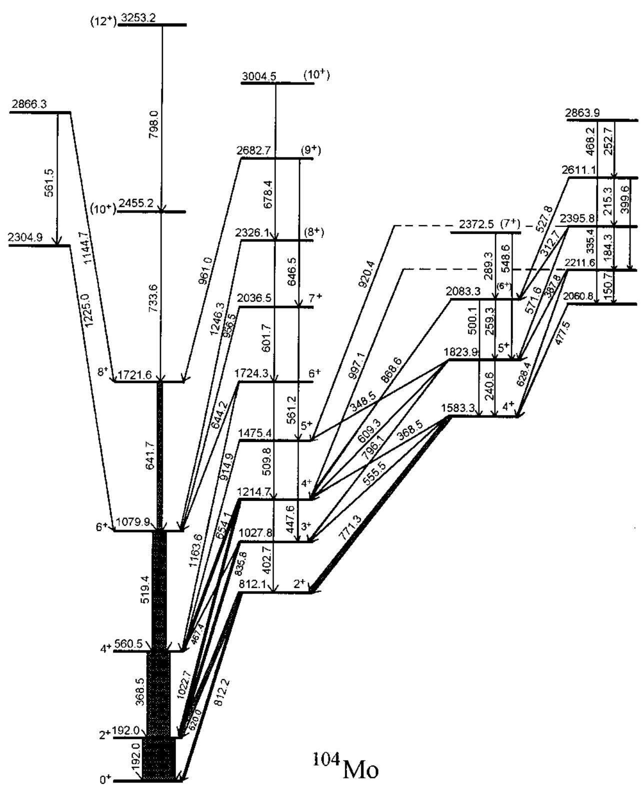

FIG. 3. Partial decay scheme for ^{104}Mo. The relative intensity of a transition is proportional to the thickness of the line representing it.

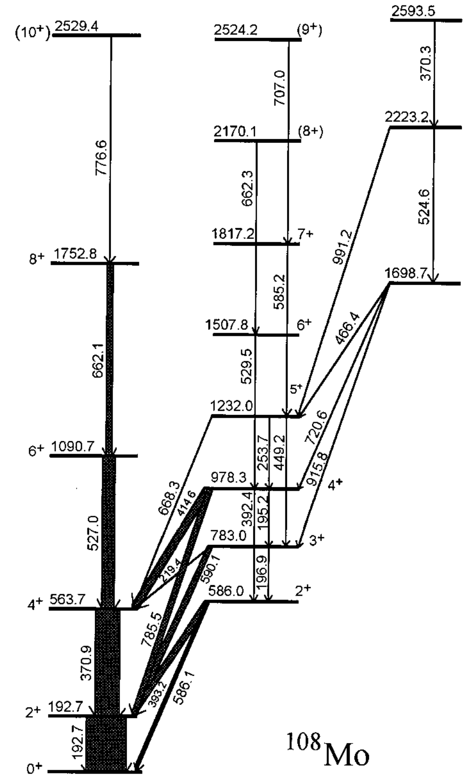

FIG. 4. Partial decay scheme for ^{108}Mo. The relative intensity of a transition is proportional to the thickness of the line representing it.

III. DISCUSSION

^{104}Mo, with an $E_{4_1^+}/E_{2_1^+}$ ratio of 2.92, lies in a region of deformation where level patterns and transition probabilities have been interpreted in terms of rigid rotation, alternatively for axially or triaxially shaped nuclei. On the assumption of a rigid nonaxial rotor, the value of the nonaxiality parameter deduced from the $E_{2_2^+}/E_{2_1^+}$ ratio, γ=18.8°, differs slightly from the value γ=20.4(5)° deduced from the γ-branching ratio of the 2_2^+ level. Excitation energies are calculated within this model, using the formulas of Ref. [9]. Table III shows that if the excitation energies are fairly well reproduced at low energy, the calculations for the high-spin states associated with the axially asymmetric rotor do not reproduce the experimental level pattern. In the same way agreement between experiment and theory is not complete for electromagnetic transition strengths: the model [9,10] reproduces nearly the branching ratios for the 2_1^+,3_1^+, and 5_1^+ states, but calculations deviate from experiment for the 4_2^+ state, as shown in Fig. 5.

TABLE II. γ branching ratios in ^{104,106,108}Mo.

Nucleus	Level (keV)	E_γ (keV)	γ branching (%)
^{104}Mo	812.1	620.0	60(3)
		812.2	40(3)
	1027.8	467.4	11(1)
		835.8	89(1)
	1214.7	402.7	25(5)
		654.1	49(7)
		1022.6	26(5)
	1475.4	447.6	35(2)
		914.9	65(2)
	1583.3	368.5	16(3)
		555.5	36(2)
		771.3	48(2)
	1724.3	509.8	45(3)
		644.2	34(3)
		1163.6	21(2)
	1823.9	240.6	20(2)
		348.5	9(3)
		609.3	35(3)
		796.1	36(2)
	2036.5	561.2	69(3)
		956.5	31(3)
	2083.3	259.3	32(4)
		500.1	27(5)
		868.6	41(5)
	2211.6	150.7	27(2)
		387.8	35(3)
		628.6	31(2)
		997.1	7(2)
	2326.1	601.7	82(4)
		1246.3	18(4)
	2395.8	184.3	47(3)
		312.7	6(1)
		335.4	11(1)
		571.6	36(2)
	2611.1	215.3	57(5)
		399.6	17(4)
		527.8	26(4)
^{106}Mo	710.4	538.9	50(2)
		710.4	50(2)
	884.9	174.6	1.1(3)
		362.7	8(3)
		713.4	92(3)
	1067.6	357.2	16(2)
		545.5	45(1)
		896.1	39(2)
	1306.3	239.2	4(1)
		421.3	36(2)
		784.4	60(2)
	1434.6	367.0	7(1)
		549.6	42(2)
		724.3	51(2)
	1563.3	495.7	54(4)
		529.9	29(3)
		1041.3	17(3)
	1657.3	222.9	15(2)
		350.4	8(2)
		589.9	29(4)
		772.3	48(3)
	1910.0	252.3	27(2)
		475.6	17(2)
		603.5	24(3)
		842.5	32(3)
	1936.6	869.1	33(3)
		1051.6	67(3)
	2142.0	190.2	31(7)
		484.5	69(7)
	2199.2	289.2	25(7)
		542.0	75(7)
	2276.0	339.2	22(2)
		713.1	30(3)
		969.4	37(3)
		1243.0	11(2)
	2368.4	226.3	43(3)
		416.7	35(3)
		458.2	22(2)
	2628.5	260.1	24(2)
		429.1	13(2)
		486.6	63(3)
^{108}Mo	586.0	393.2	65(7)
		586.1	35(7)
	783.0	196.9	15(1)
		219.4	7(1)
		590.1	78(2)
	978.3	195.2	5(2)
		392.4	32(4)
		414.6	35(4)
		785.5	28(3)
	1232.0	253.7	5(1)
		449.2	67(2)
		668.3	28(2)
	1698.7	466.4	17(3)
		720.6	32(4)
		915.8	51(5)

A more appropriate description of ^{104}Mo is to consider it as an axially symmetric nucleus. The level sequence starting at 812.1 keV is then identified as the rotational band based on the one phonon γ-vibrational state at 812.1 keV. This is supported by the fact that the ground state and the one phonon γ-band exhibit, as expected, similar moments of inertia (see the inertia parameters A for both bands in Table IV). Assuming identical intrinsic quadrupole moments within the ground state band and the γ band and taking into account the rotation-vibration interaction, the interband $B(E2)$ value may be written [11]

TABLE III. Excitations energies (keV) in ^{104}Mo. Experimental values and values predicted by the rigid triaxial rotor model with $\gamma = 20.4°$. (*) Normalization.

Yrast Band		Lowest side band	
Expt.	Theor.	Expt.	Theor.
192	180	812	643
561	557	1028	823
1080	1080*	1215	1122
1722	1739	1475	1363
2455	2539	1724	1920
3253	3483	2037	2111
		2326	3008
		2683	3041
		3005	4318

$$B(E2;K=2,I_i \rightarrow K=0,I_f) = 2M_1^2 \langle I_i 2 2 -2 | I_f 0 \rangle^2 \{1 + a_2 [I_f(I_f+1) - I_i(I_i+1)]\}^2 \qquad (1)$$

where $a_2 = -M_2/M_1$ and M_1 and M_2 are intrinsic interband matrix elements, M_2 containing the rotation-vibration coupling strength. The quantity a_2 can be considered as an adjustable parameter and be deduced from ratios of reduced transition probabilities, under the assumption that the transitions between the $K=2$ and $K=0$ bands are predominantly $E2$ radiations, as suggested by the K-selection rule and as observed in the lighter ^{98}Mo and ^{100}Mo isotopes [12,13]. Using the average value $a_2 = 0.062(2)$, and Eq. (1), calculated $B(E2)$ ratios have been obtained for the interband transitions. The experimentally determined $B(E2)$ ratios and the calculated ratios are given in Table V. The agreement supports the axially symmetric description of the nucleus.

It has been shown recently that the 1434.6 keV level in ^{106}Mo is an excellent candidate for a harmonic double phonon γ-vibrational state [1]. If in a similar manner one considers the 1583.3 keV level in ^{104}Mo as a potential two phonon γ-vibrational state, the ratio of the intrinsic energies of the band heads, $E_{K=4}/E_{K=2}$, is equal to 1.87 indicating that anharmonic effects are present in the vibrational mode. Doing the same kind of calculations as in [1], one may extract from the measured branching ratios the following quantity:

TABLE IV. Rotational energy parameters in ^{104}Mo and ^{108}Mo. The parameters are deduced from fits to the bands using the second order rotational energy formula $E(I,K) = E_K + A[I(I+1) - K^2] + B[I(I+1) - K^2]^2$. (*) Fits to the band based on the 2061 keV state with different assumptions on the K value.

Nucleus	K	E_K (keV)	A (keV)	B (eV)
^{104}Mo	0	29	26.1	−36
	2	794	26.8	−57
	4_1	1487	24.8	−66
	4_2^*	2001	14.9	83
	5*	1999	12.3	153
^{108}Mo	0	20	27.1	−40
	2	552	27.1	−49

$$\langle K=2, n_\gamma=1 | M(E2,\Delta K) | K=4, n_\gamma=2 \rangle / \langle K=0, n_\gamma=0, | M(E2,\Delta K) | K=2, n_\gamma=1 \rangle,$$

where n_γ is the number of aligned γ-vibrational phonons in the intrinsic state. The experimental ratio of 1.54(22) compares favorably with the ratio $\sqrt{2}$ expected for rotational bands built on pure γ-vibrational states.

As for ^{104}Mo, the yrast band and the γ band in ^{108}Mo have similar inertia parameters A (see Table IV). Such a picture is forseen for quadrupole vibrational excitations since the moment of inertia is not expected to be altered greatly through small oscillations around the ground state shape. However, for this isotope no candidate for a harmonic double phonon γ-vibrational state has been observed in the present study. Note that ^{108}Mo is less populated in the spontaneous fission of ^{248}Cm than ^{104}Mo or ^{106}Mo.

The best fits of the band based on the state at 2060.8 keV excitation energy in ^{104}Mo to the second order rotational formula are obtained for $K=4$ and 5. The band head most probably has a quasiparticle configuration. Indeed, moments of inertia of two-quasiparticle bands are systematically larger (and consequently their inertia parameters smaller) than the moments of the ground state bands and this is effectively observed in the present case, as can be seen in Table IV. Knowing that a $\beta_2 = 0.31$ value has been inferred for ^{104}Mo from the lifetime measurement of the 2_1^+ state [14],

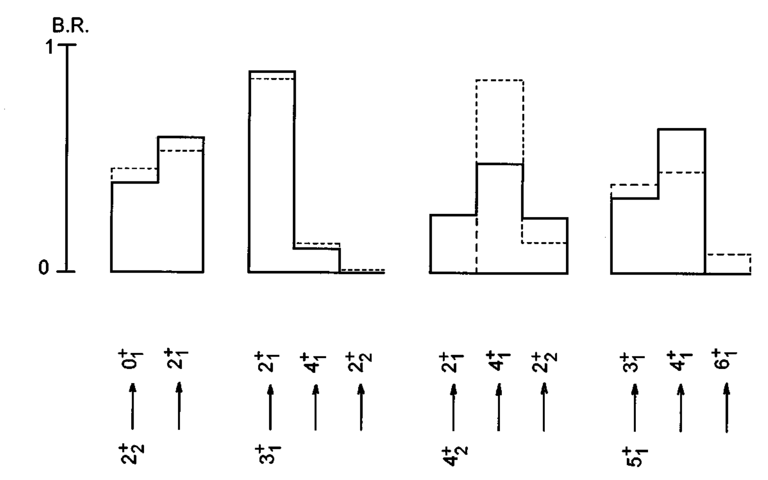

FIG. 5. Comparison of experimental γ-branching ratios in ^{104}Mo (full lines) and values calculated within a simple rigid triaxial rotor model (dashed lines).

TABLE V. Experimentally determined $B(E2)$ ratios and calculated ratios for interband $K=2\rightarrow K=0$ transitions in ^{104}Mo.

Transitions involved	Experiment	Theory
$(2_2^+\rightarrow 0_1^+)/(2_2^+\rightarrow 2_1^+)$	0.173(16)	0.276(11)
$(3_1^+\rightarrow 2_1^+)/(3_1^+\rightarrow 4_1^+)$	0.443(41)	0.441(26)
$(4_2^+\rightarrow 2_1^+)/(4_2^+\rightarrow 4_1^+)$	0.0098(27)	0.0062(25)
$(6_2^+\rightarrow 4_1^+)/(6_2^+\rightarrow 6_1^+)$	0.032(4)	0.036(9)

Nilsson diagrams for protons and neutrons [3] may suggest several configurations for the 2060.8 keV level with $K=4$ or 5: the $\pi\{[422]5/2^+[303]5/2^-\}5^-$, the $\nu\{[411]3/2^+[532]5/2^-\}4^-$, or the $\nu\{[411]3/2^+[413]5/2^+\}4^+$ configurations. The identification of the proper configuration could eventually be obtained by comparing the intrinsic g factor extracted from the γ branching in the rotational band built on the quasiparticle state to the one calculated using g factors from well defined bands in odd-A nuclei. Indeed for a stretched configuration with $K=K_1+K_2, Kg_K=K_1g_{K_1}+K_2g_{K_2}$. More precisely, the quantity deduced from branching ratios is the difference between the intrinsic and rotational g factors over the intrinsic quadrupole moment

$$|(g_K-g_R)/Q_0|=0.934E_\gamma|\delta|^{-1}[(I+1)(I-1)]^{-1/2}\ \ (e\ \mathrm{b})^{-1},$$

where E_γ is the energy of the $I\rightarrow I-1$ transition. The mixing ratio δ^2 is deduced from the following formula:

$$1+\delta^{-2}=(I_\gamma/I_{\gamma'})(E_{\gamma'}/E_\gamma)^5(I+1)(I+K-1)(I-K-1)\times[2K^2(2I-1)]^{-1},$$

where $E_{\gamma'}$ and $I_{\gamma'}$ are respectively the energy and intensity of the $I\rightarrow I-2$ crossover transition. For the band based on the 2060.8 keV level, the average value for $|(g_K-g_R)/Q_0|$ is 0.12(2) $(e\ \mathrm{b})^{-1}$ if $K=4$. It has to be compared to the value 0.15 $(e\ \mathrm{b})^{-1}$ calculated for a $K^\pi=4^-$ band using the experimental values of $|(g_K-g_R)/Q_0|$ deduced from the ground-state band of ^{101}Zr for the $\nu[411]3/2^+$ configuration and from the sideband in ^{101}Zr and the ground-state band in ^{103}Zr for the $\nu[532]5/2^-$ configuration [3]. No experimental value of $|(g_K-g_R)/Q_0|$ is known for the $\nu[413]5/2^+$ configuration. However, calculations predict g_K and g_R to nearly cancel each other [3], setting a lower limit of 0.07 $(e\ \mathrm{b})^{-1}$ on the $|(g_K-g_R)/Q_0|$ value for $K^\pi=4^+$ band. In the case of $K=5$, the average value for $|(g_K-g_R)/Q_0|$ is 0.09(2) $(e\ \mathrm{b})^{-1}$, whereas a value of 0.15 $(e\ \mathrm{b})^{-1}$ is deduced from the γ branchings in the ground-state bands in ^{101}Nb and ^{103}Nb and the lowest sideband in ^{103}Nb for the proton quasiparticle state with a stretched $K^\pi=5^-$ configuration. So the existing data suggest that the 2060.8 keV level has a neutron configuration, but they are unable to discriminate between the two suggested configurations.

IV. SUMMARY

A detailed study of prompt γ rays emitted by Mo fragments produced in the spontaneous fission of ^{248}Cm results in the extension of the level schemes of ^{104}Mo and ^{108}Mo. They consist primarily of rotational bands observed up to moderately high spins and built on the ground state, the one-phonon state and, for ^{104}Mo, also on the two-phonon γ-vibrational state and a quasiparticle state. The experimental results can be reproduced satisfactorily within a description of ^{104,108}Mo as axially symmetric nuclei.

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