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Near-yrast, medium-spin structure of the ^{107}Mo nucleus

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Excited states in ^{107}Mo, populated in spontaneous fission of ^{248}Cm, were studied by use of the EUROGAM2 multidetector array. Spins and parities of the ground state and the 66.0-, 152.1-, and 458.5-keV excited levels, reported previously, were changed based on conversion-coefficient and angular-correlation measurements. Octupole deformation reported previously in ^{107}Mo is dismissed, and we explain the near-yrast structure of ^{107}Mo in terms of rotational bands built on the $5/2^+[413]$, $3/2^+[411]$, and $7/2^-[523]$ orbitals.

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The experimental data for many neutron-rich, odd-*A* nuclei from the mass $A = 110$ region are rather consistent with the Nilsson diagrams for both protons and neutrons, calculated in a prolate potential [1–5]. Deviations toward triaxiality for Mo and Ru isotopes [6–9] and a possible transition from prolate to oblate shape around $N = 68$ [10–12] were also discussed.

There is, however, a distinct exception for ^{107}Mo and ^{109}Mo. In Ref. [13], the near-yrast excitations in these nuclei were described as being due to static octupole deformation. Octupole correlations in ^{107}Mo and ^{109}Mo were reported as strong and of a new type, resulting from interactions between protons only.

Octupole effects are not reported in the ^{105}Mo nucleus [1,13], and the authors of Ref. [13] agree that there is no octupole deformation in ^{106}Mo and ^{108}Mo. Our recent study [11] indicates that there is also no octupole deformation in ^{110}Mo. The presence of octupole deformation just in the ^{107}Mo and ^{109}Mo nuclei would require particularly strong octupole correlations between protons, enhanced by odd neutrons at $N = 65$ and $N = 67$.

The knowledge of nuclear deformation in this region is of importance because of the question of how it evolve with increasing neutron number when approaching the path of the astrophysical *r* process [14]. It is therefore of interest to verify the information on octupole deformation in ^{107}Mo and ^{109}Mo.

We studied the ^{107}Mo nucleus, populated in spontaneous fission of ^{248}Cm. Prompt γ rays following fission were measured with the EUROGAM2 array with four additional low-energy photon (LEP) detectors (for more details on the experiment see [15–17]). The data obtained in this work allowed a new interpretation of excited states in ^{107}Mo, as subsequently discussed.

We confirm coincidence relations between γ rays and the energies of excited levels in ^{107}Mo reported in Ref. [13]. In particular we agree that there is a level at 166 keV [13], and the 326-keV transition reported in [1] on top of the 66-keV level feeds the 165.4-keV level. However, we found new γ lines in ^{107}Mo, that allow the change of the band structure proposed in [13]. Their presence is documented in Fig. 1.

A spectrum, double gated on the 152.1-keV line in ^{107}Mo and the 588.9-keV line in ^{138}Xe [18], the strongest fission partner to ^{107}Mo, is shown in Fig. 1(a). In the spectrum, new lines at 188.9, 225.6, 240.9, and 478.8 keV are seen. A double gate on the new 478.8-keV line and 588.9-keV line of ^{138}Xe, seen in Fig. 1(b), shows the 152.1- and 188.9-keV lines and a new line at 341.0 keV. The double gate on the new 240.9-keV line and the 588.9-keV line, displayed in Fig. 1(c), shows the 152.1-, 188.9-, and 341.0-keV lines and the 405.9- and 557.5-keV lines of the yrast cascade. Therefore we introduce a new level at 341.0 keV. It is populated by the 240.9-keV transition from the known 581.9-keV level and decays by the 188.9- and 341.0-keV transitions to the 152.1-keV level and the ground state, respectively. The 152.1–188.9-keV double gate in Fig. 1(d) shows a new line at 225.6 keV, which is a new decay branch of the the 566.6-keV level reported previously [1,13].

The 478.8-keV transition feeding the 341.0-keV level defines a new level at 819.8 keV, decaying by the 253.4-keV transition to the 566.6-keV level. The 341.0–478.8-keV double gate, displayed in Fig. 1(e), shows new lines at 602.8 and 720 keV, the latter with large broadening characteristic of an in-band, $E2$ transition depopulating rotational states with spin of 10–12 spin units [19]. Based on these and further coincidence relations we introduce new levels at 1422.7 and 2143 keV.

We add to the level scheme the 152-, 555.0-, 709-, and the 790-keV transitions, extending the yrast band reported in [1,13]. We also see very broad distributions centered at 943 and 1043 keV, which most likely correspond to the 942.8- and 1041.2-keV transitions reported in a recent work [20].

The partial level scheme of ^{107}Mo obtained in this work is shown in Fig. 2. Spins and parities were determined based on angular-correlation, linear-polarization, and

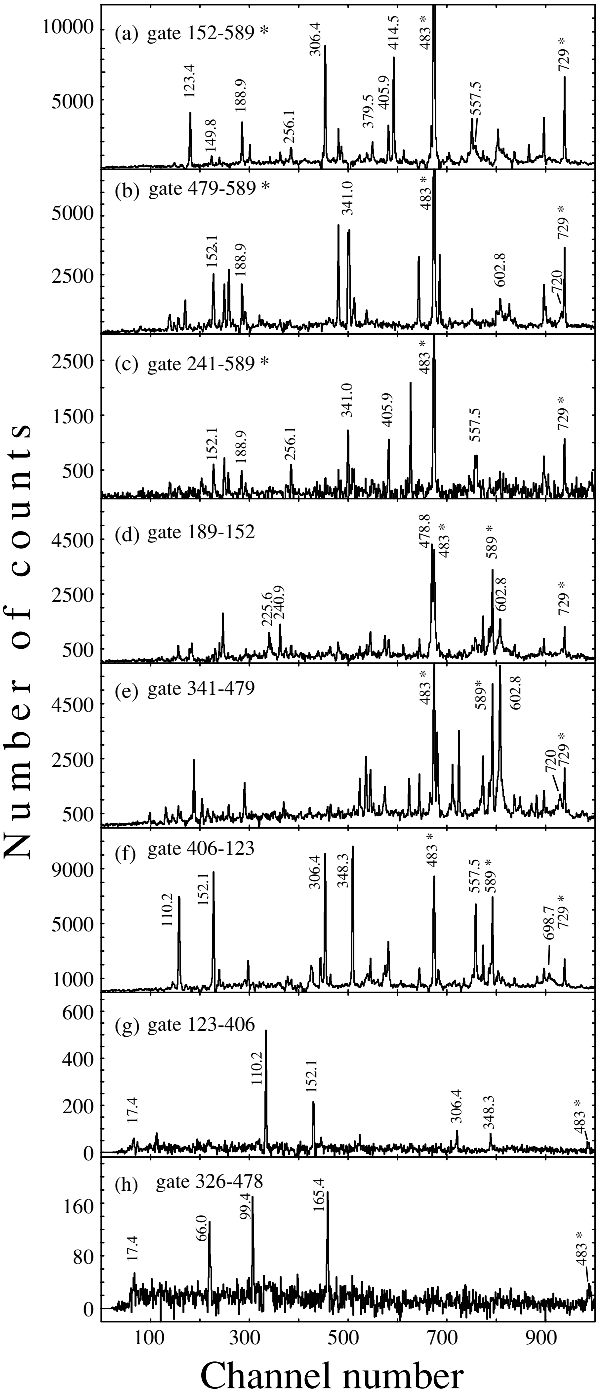

FIG. 1. Coincidence spectra gated on γ lines in ^{107}Mo and ^{138}Xe. Energies of lines are given in kilo-electron-volts. Panels a–f show spectra measured by a Ge detector of EUROGAM, and panels g and h show spectra measured by a LEP. The symbol $*$ denote lines in ^{138}Xe. Strong unlabeled lines are from contaminating nuclei.

conversion-electron coefficients measured in this work, using techniques described in [16,17]. The results of those measurements are listed in Table I and in the subsequent text, where we discuss some essential assignments.

TABLE I. Angular correlations and proposed multipolarities for transitions in the ^{107}Mo nucleus as obtained in this work.

$E_{\gamma 1} - E_{\gamma 2}$ (keV–keV)	A_2/A_0	A_4/A_0	Multipolarities of γ_1 , γ_2 transitions
66.0–253.7	−0.03(2)	0.04(3)	$\Delta I = 1, \Delta I = 2$
99.4–326.3	−0.05(2)	0.05(4)	$\Delta I = 1, \Delta I = 2$
110.2–379.5	−0.06(2)	0.04(3)	$\Delta I = 1, \Delta I = 2$
123.4–405.9	−0.07(2)	0.02(3)	$\Delta I = 1, \Delta I = 2$
149.8–379.5	−0.01(2)	0.01(3)	$\Delta I = 1, \Delta I = 2$
152.1–414.5	−0.04(2)	−0.07(4)	$\Delta I = 1, \Delta I = 2$
152.1–306.4	0.10(3)	−0.06(4)	$\Delta I = 1, \Delta I = 1$
154.3–410.8	−0.07(3)	−0.01(4)	$\Delta I = 1, \Delta I = 2$
165.4–326.4	0.04(2)	0.01(3)	$\Delta I = 0, \Delta I = 2$
171.9–253.7	−0.02(1)	0.09(4)	$\Delta I = 1, \Delta I = 2$
188.9–152.1	0.06(3)	0.04(4)	$\Delta I = 1, \Delta I = 1$
233.6–405.9	0.09(2)	−0.04(2)	$\Delta I = 2, \Delta I = 2$
256.1–233.6	−0.05(2)	−0.01(3)	$\Delta I = 1, \Delta I = 2$
306.4–379.5	−0.06(2)	0.02(3)	$\Delta I = 1, \Delta I = 2$
326.3–477.9	0.06(3)	−0.02(4)	$\Delta I = 2, \Delta I = 2$
341.0–478.8	0.07(3)	−0.02(5)	$\Delta I = 2, \Delta I = 2$
348.3–233.6	−0.10(2)	0.01(3)	$\Delta I = 1, \Delta I = 2$
379.5–555.0	0.05(2)	−0.02(4)	$\Delta I = 2, \Delta I = 2$
405.9–557.6	0.10(3)	−0.01(4)	$\Delta I = 2, \Delta I = 2$
410.8–253.7	0.07(3)	−0.01(4)	$\Delta I = 2, \Delta I = 2$
478.8–602.8	0.04(1)	−0.04(5)	$\Delta I = 2, \Delta I = 2$
551.2–414.5	0.09(3)	0.01(4)	$\Delta I = 2, \Delta I = 2$
557.6–698.7	0.07(3)	−0.01(4)	$\Delta I = 2, \Delta I = 2$
679.0–551.2	0.05(3)	0.00(4)	$\Delta I = 2, \Delta I = 2$

In the band based on the 348.3-keV level angular correlations between 233.6- and 348.3-keV lines indicate a $\Delta I = 1$ character of one of them and a $\Delta I = 2$ of the other. Angular correlations for the 233.6–405.9-keV cascade indicate $\Delta I = 2$ for both transitions. Therefore we assign the $\Delta I = 1$ change in spin to the 348.3-keV transition. Our data are consistent with the $\Delta I = 2$ character of the 379.5-, 555.0-, 557.5-, and 698.7-keV transitions and the $\Delta I = 1$ character of the 110.3-, 123.4-, 149.8-, 256.1-, and 306.4-keV lines.

The 110.2-, and 123.4-keV transitions were reported in [13] as $E1$. Figure 1(f) shows a spectrum double gated on the 405.9- and 123.4-keV lines. From the intensity balance for the 110.2- and 348.3-keV lines, seen in the spectrum, the total conversion coefficient α_T of the 110.2-keV line can be obtained. An average $\alpha_T = 0.22(4)$, obtained from this and other double gates (123.4–256.1, 123.4–588.9, 379.5–555.0) should be compared with theoretical α_t values at 110 keV of 0.09 for $E1$, 0.19 for $M1$, and 0.84 for an $E2$ multipolarities.

We also estimated the α_K coefficient. In Fig. 1(g) a spectrum measured by the LEP detector, gated on the 123.4- and 405.9-keV lines, is shown, where the 110.2-keV line and the K$_\alpha$ x-ray line of Mo at 17.4 keV are seen. The resulting coefficient is $\alpha_K = 0.9\ ^{+0.7}_{-0.4}$, which should be compared with theoretical values at 110 keV of 0.1 for $E1$, 0.2 for $M1$, and 0.7 for $E2$ transitions.

Analogous procedures are given for the 123.4-keV transition conversion coefficients of $\alpha_t = 0.27(8)$ and $\alpha_K = 0.8\ ^{+0.7}_{-0.4}$. Therefore, our results clearly indicate an $M1 + E2$ multipolarity of the 110.3- and 123.4-keV transitions.

The 348.3-keV band in ^{107}Mo closely resembles the 7/2$^-$[523] band in ^{111}Ru [9]. In Fig. 3 we show staggering

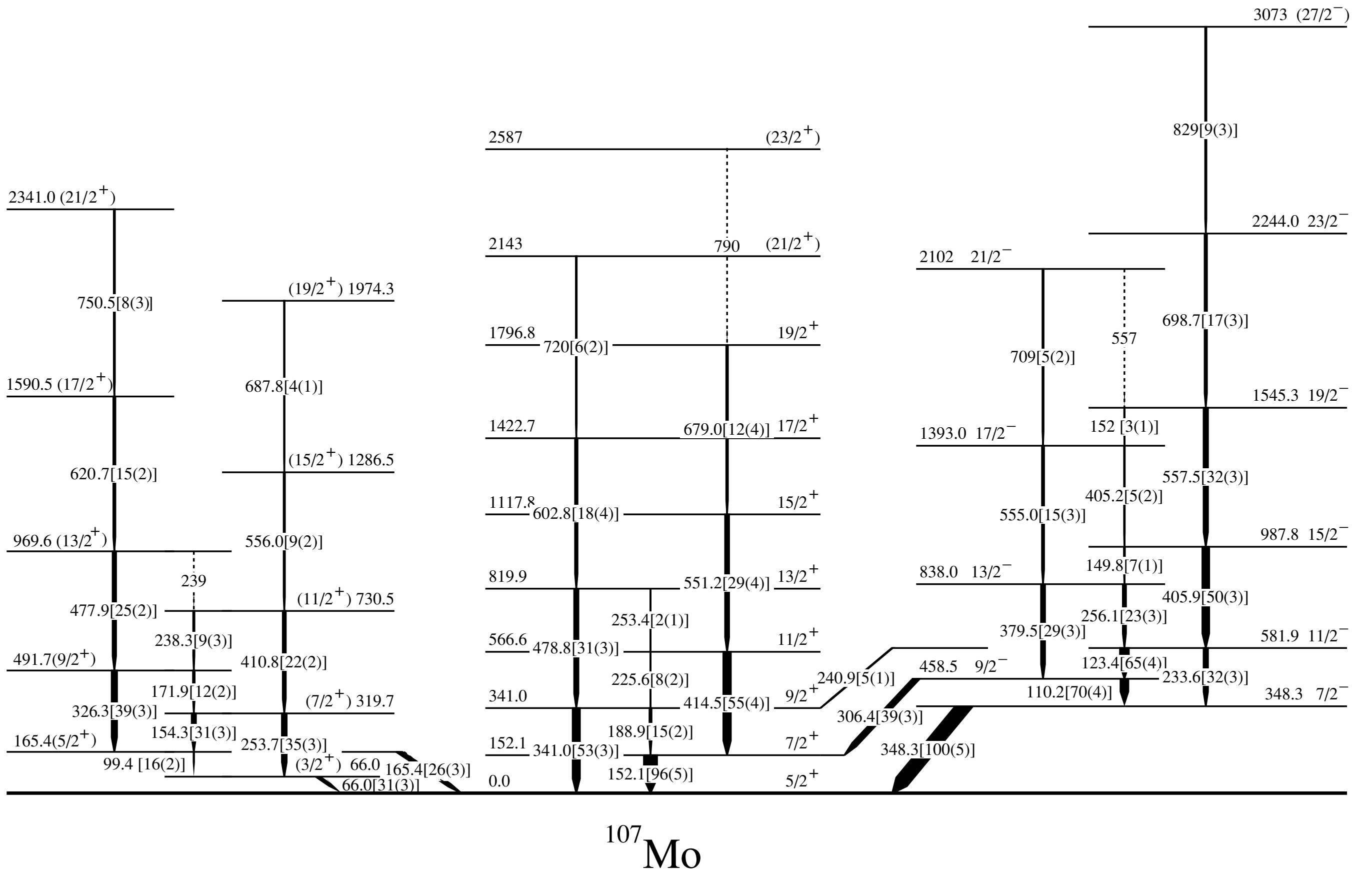

FIG. 2. Partial level scheme of ^{107}Mo as obtained in this work. Relative γ intensities (with error bars) are given in square brackets. Uncertainties on γ energies range from 0.1 keV for strong lines up to 0.5 keV for weak lines.

in both bands, where we assigned spin $7/2^-$ to the 348.3-keV bandhead in ^{107}Mo. The observed similarity supports such a spin assignment and suggests that this band corresponds to the $7/2^-[523]$ neutron orbital.

The pattern of the 348.3-keV band is characteristic of a decoupled, rotation-aligned configuration. In Fig. 4 we show spin alignment I_x in this band, calculated as a function of the rotational frequency ω from the usual formula $I_x = \sqrt{(I_a + 1/2)^2 - K^2}$, where $I_a = (I_i - I_f)/2, \hbar\omega = (E_i - E_f)/2$ and we assumed $K = 7/2$. A difference of one unit in alignment between the two signature branches is a characteristic feature of a decoupled band.

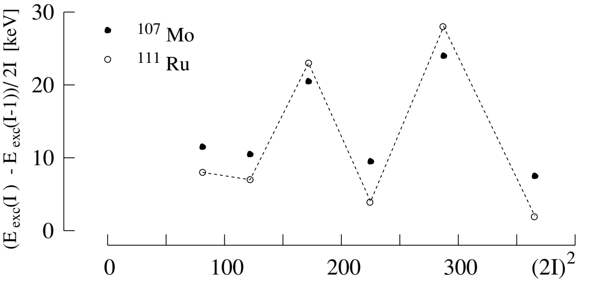

FIG. 3. Staggering in the negative-parity bands of ^{107}Mo and ^{111}Ru [9]. The dashed line is drawn to guide the eye.

The single-particle alignment i in the 348.3-keV band can be estimated from the difference between I_x values for this band and the $K = 0$, ground-state band in ^{106}Mo. In the range of $\hbar\omega$ from 200 to 400 keV the single-particle alignment has values of $i \approx 1.1\hbar$ for the $\alpha = 1/2$ and $i \approx 2.2\hbar$ for the $\alpha = -1/2$ signature branches. Their sum, $i \approx 3.4\hbar$ equals the alignment in the S band of the ^{106}Mo core [7]. This result supports

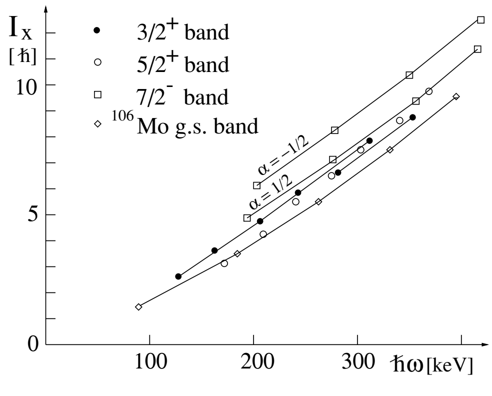

FIG. 4. Total angular momentum alignment I_x for bands in ^{107}Mo and the ground-state (g.s.) band in ^{106}Mo. Lines are drawn to guide the eye. See text for more explanations.

further the $7/2^-$ spin and parity assignments to the 348.3-keV level.

We measured polarization-directional correlations [16] for the 348.3-keV line in a cascade with the 233.6-keV $E2$ line. The obtained polarization $P = +0.30(14)$ and angular correlations indicate a stretched $E1$ multipolarity of the 348.3-keV transition. This result, the $7/2^-$ spin and parity of the 348.3-keV level, and the observed band population indicate spin and parity $5/2^+$ to the ground state of ^{107}Mo, reported as $7/2^-$ in [13].

In the ground-state band the 341.0-, 414.5-, 478.8-, 551.2-, 602.8-, and 679-keV lines correspond to $\Delta I = 2$ and the 152.1- and 188.9-keV lines to $\Delta I \leqslant 1$ spin change, as indicated by our angular correlations. We note that the 152.1-keV line is not a $\Delta I = 2$, as suggested in [13].

We determined the α_T coefficient for this line from the intensity balance of the 152.1- and 306.4-keV lines observed in the doubly gated spectrum shown in Fig. 1(f). The resulting $\alpha_T = 0.34(7)$ should be compared with theoretical values of 0.04, 0.08, and 0.27 for $E1, M1$, and $E2$ multipolarites, respectively. This and the angular correlation for the 152.1-keV line indicate its $M1 + E2$ multipolarity and, consequently, spin and parity $7/2^+$ for the 152.1-keV level, rather than $11/2^-$ as reported in [13].

The ground-state band in ^{107}Mo forms a $\Delta I = 1$ band. The $I_x(\omega)$ for this band, calculated with $K = 5/2$ and displayed in Fig. 4 (open circles), shows a small single-particle alignment, $i \leqslant 1\hbar$. Two orbitals, $5/2^+[413]$ and $5/2^+[402]$, can produce in ^{107}Mo spin $I^\pi = 5/2^+$ and low alignment. Following the calculation procedure from Ref. [21], we estimated $|g_K - g_R|/Q_0$ values in the ground-state band from the γ-ray branching ratios and calculated experimental $g_K(5/2^+) = +0.22(3)$, taking $Q_0 = 3$ b and $g_R = 0.3$. Theoretical estimates g_K^{th} can be calculated with the formula

$$g_K = g_l + \frac{(g_s - g_l)}{2K}\text{GMS}(K \rightarrow K),$$

where $g_s = 0.6 g_s(\text{free}) = -2.296$ [22] and $\text{GMS}(K \rightarrow K)$ is a quantity dependent on deformation parameter β, tabulated in Ref. [22]. Taking $\beta = 0.3$ and $g_l = 0$ we obtained $g_K^{\text{th}}(5/2^+[413]) = +0.36$ and $g_K^{\text{th}}(5/2^+[402]) = -0.45$. The experimental value compared against the theoretical estimates clearly indicates the $5/2^+[413]$ assignment for the ground-state configuration of ^{107}Mo. A similar assignment was made for the ground state in ^{111}Ru [9,23].

In the band on top of the 66.0-keV level, the 253.7-, 326.3-, 410.8-, and 477.9-keV transitions are $\Delta = 2$ whereas the 99.4-, 154.3-, and 171.9-keV in-band transitions as well as the 66.0- and 165.4-keV out-of-band transitions are $\Delta I \leqslant 1$ in character. The $\alpha_K = 1.8^{+0.5}_{-1.0}$ coefficient for the 66.0-keV transition [1] is confirmed in this work, with $\alpha_K = 1.6^{+0.7}_{-0.8}$ suggesting $M1 + E2$ multipolarity for this transition.

In Fig. 1(h) we show a LEP spectrum, double gated on the 326.3- and 477.9-keV lines, where the 66.0- and 99.4-keV lines are seen. Their total intensities should be equal in this spectrum. The observed ratio of γ intensities, $I_\gamma(66.0)/I_\gamma(99.4) = 0.95(15)$, is close to unity. This suggests similar values of their total conversion coefficients and, consequently, an $M1 + E2$ character of the 99.4-keV line. Otherwise, if the 99.4-keV line is an $E1$, as reported in [13], and the 66.0-keV line is $M1 + E2$ as previously shown, one should get a much smaller ratio of intensities in this spectrum, $I_\gamma(66.0)/I_\gamma(99.4) \leqslant 0.2$.

Our angular correlations are consistent with spin 3/2 or 5/2 for the 66.0-keV bandhead. The 3/2 spin assignment is favored by the alignment analysis. In Fig. 4 we show, the I_x for the band calculated with $K = 3/2$. An alignment $i \leqslant 1$, calculated relative to the ^{106}Mo core, is consistent with the interpretation of this band as the $3/2^+[411]$ neutron configuration. The assumption of $K = 5/2$ leads to an alignment $i = 1.5$, which is difficult to account for with the available $5/2^+[413]$ and the $5/2^+[402]$ orbitals. We note that the $3/2^+[411]$ configuration is observed near the ground state in ^{105}Mo [2].

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