Identification of a high-spin isomer in ^{99}Mo

G. A. Jones,[1,*] P. H. Regan,[1] P. M. Walker,[1] Zs. Podolyák,[1] P. D. Stevenson,[1] M. P. Carpenter,[2] J. J. Carroll,[3] R. S. Chakrawarthy,[4] P. Chowdhury,[5] A. B. Garnsworthy,[1] R. V. F. Janssens,[2] T. L. Khoo,[2] F. G. Kondev,[6] G. J. Lane,[7] Z. Liu,[1] D. Seweryniak,[2] N. J. Thompson,[1] S. Zhu,[2] and S. J. Williams[1,4]

[1]*Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom*
[2]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[3]*Department of Physics and Astronomy, Youngstown, Ohio 44555, USA*
[4]*TRIUMF, 4004 Westbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*
[5]*University of Massachusetts Lowell, Lowell, Massachusetts 01854, USA*
[6]*Nuclear Engineering Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[7]*Department of Nuclear Physics, RSPhysSE, Australian National University, Canberra 0200, Australia*

(Received 16 February 2007; revised manuscript received 26 April 2007; published 2 October 2007)

A previously unreported isomer has been identified in ^{99}Mo at an excitation energy of $E_x = 3010$ keV, decaying with a half-life of $T_{1/2} = 8(2)$ ns. The nucleus of interest was produced following fusion-fission reactions between a thick ^{27}Al target frame and a ^{178}Hf beam at a laboratory energy of 1150 MeV. This isomeric state is interpreted as an energetically favored, maximally aligned configuration of $\nu h_{\frac{11}{2}} \otimes \pi(g_{\frac{9}{2}})^2$.

DOI: 10.1103/PhysRevC.76.047303 PACS number(s): 21.10.Dr, 23.20.Lv, 27.60.+j, 25.70.Jj

The near-yrast structure of the $A \sim 100$ region with $N \geqslant 56$ is dominated by excitations associated with the high-j "unnatural parity" proton $g_{\frac{9}{2}}$ and neutron $h_{\frac{11}{2}}$ orbitals. Decoupled, rotational sequences built on a single $\nu h_{\frac{11}{2}}$ orbital are observed in all $N = 57$ isotones from $^{99}_{42}$Mo up to $^{109}_{52}$Te [1–7] with associated weakly deformed, prolate shapes. At medium spins, these single-quasiparticle rotational bands are crossed by multi-quasiparticle configurations, which have been interpreted in the framework of the Cranked Shell Model to be associated with either $\nu h_{\frac{11}{2}} \otimes \pi(g_{\frac{9}{2}})^2$, $\nu h_{\frac{11}{2}} \otimes \nu(g_{\frac{7}{2}})^2$, or $\nu h_{\frac{11}{2}} \otimes \nu(h_{\frac{11}{2}})^2$ configurations, depending on the proton number and the associated core deformation [1–3]. These collective rotational bands can compete with single-particle excitations formed by the favored, maximally aligned couplings of high-j proton ($g_{\frac{9}{2}}$) and neutron ($h_{\frac{11}{2}}$ and $g_{\frac{7}{2}}$) orbitals. This Brief Report describes the identification of a high-spin isomeric state that feeds the previously reported $h_{\frac{11}{2}}$ decoupled-rotational structure, at $I^\pi = \frac{23}{2}^-$, in ^{99}Mo [1].

The experiment was performed at Argonne National Laboratory using the Argonne Tandem Linear Accelerator System (ATLAS), which delivered a ^{178}Hf beam at a laboratory energy of 1150 MeV, with an average beam intensity of 2 particle nA. The main experimental focus was to study long-lived isomers in hafnium-like nuclei, using deep-inelastic reactions with a thick ^{208}Pb target; the results from this work are reported in Ref. [8]. The data on ^{99}Mo described in this Brief Report were obtained from incidental fusion-fission reactions between the ^{178}Hf projectiles and the ^{27}Al support frame for the ^{208}Pb target. Nuclei synthesized in fusion-fission reactions were identified as such from the observation of γ rays associated with the decay of binary products, consistent with the fission of the ^{178}Hf + ^{27}Al fusion-compound nucleus. The beam delivered by the ATLAS was bunched into short pulses of width $\sim$0.5 ns, separated by periods of 82.5 ns. This pulsing was utilized to study metastable states in the $10^{-9} < T_{1/2} < 10^{-4}$ s range; nine out of ten beam pulses were swept away from the target, resulting in a 825 ns period within which delayed γ-ray decays could be studied. Events where two or more coincident γ rays were detected within a 2μs range were written to tape for subsequent off-line analysis. A total of 2.1×10^9 events were recorded over the course of a 5-day experiment.

The nature of the fusion-fission reaction process leads to the detection of a plethora of γ rays emitted from excited states in a broad range of nuclei, resulting in a highly complex data set. The γ-ray decays from all the reaction products were measured using the Gammasphere [9] array, comprised of 101 Compton-suppressed germanium detectors in this experiment. Because of this level of complexity it was necessary to utilize multidimensional γ-ray coincidence techniques to correlate γ-ray decays associated with particular nuclides. A variety of coincidence cubes corresponding to different γ-ray time and energy conditions were created; Table I provides details of cubes created, which are relevant to this report. These were analyzed with standard software packages described in Refs. [10–12].

A high-spin isomer in ^{99}Mo has been observed for the first time using these data. Figure 1 provides a level scheme of transitions in ^{99}Mo deduced from the current work. The isomeric state at $E_x = 3010$ keV is observed to decay directly into the negative-parity sequence, reported in Ref. [1], by the emission of a 305 keV transition to the $I^\pi = \frac{23}{2}^-$ member of the decoupled rotational band. Figure 2(a) shows the promptly fed decays of the negative-parity band in ^{99}Mo; the 980 and 1064 keV transitions are observed from the previously reported $I^\pi = (\frac{27}{2}^-)$ and $(\frac{31}{2}^-)$ states, respectively. Figure 2(b) shows delayed transitions associated with double gates in ^{99}Mo. This spectrum clearly identifies the 482, 693, and 846 keV transitions associated with decays from the $I^\pi = \frac{15}{2}^-$, $\frac{19}{2}^-$,

*Corresponding author: G.Jones@Surrey.ac.uk

TABLE I. Three-dimensional cubes used to create the level scheme in Fig. 1 and spectra in Fig. 2. Prompt and delayed γ rays (γ_p and γ_d, respectively) are defined by the time difference, $TD_{p\,or\,d}$, between the γ-ray, T, and that of the beam, RF. The time difference between γ rays, TD_γ, is used to define transitions that are prompt with respect to each other.

	Conditions			Spectrum (see Fig. 2)	Gates ({x}{y})
	x	y	z		
1[a]	γ_p	γ_p	γ_p	(a)	{846}{482, 693}
2[b]	γ_{d1}	γ_{d1}	γ_{d1}	(b)	{846}{482, 693}
3[c]	γ_{d1}	γ_{d1}	γ_p	(c)	{482}{305, 693}
4[d]	γ_{d2}	γ_{all}	$T_{\gamma all}$	(d)	{138, 449}{305}

[a]1 - $TD_\gamma(=|T_1 - T_2|) < 30$ ns; $TD_p(=|\mathrm{RF} - T|) < 20$ ns (at $E_\gamma = 300$ keV).
[b]2 - $TD_\gamma(=|T_1 - T_2|) < 30$ ns; $TD_{d1}(=|\mathrm{RF} - T|) > 20$ ns (at $E_\gamma = 300$ keV).
[c]3 - TD_γ, TD_{d1}, & TD_p, as defined above.
[d]4 - $TD_{d2}(=|\mathrm{RF} - T|) > 90$ ns.

and $\frac{23}{2}^-$ states, respectively; there is no evidence for a 980 keV γ ray in delayed coincidence with any transitions in ^{99}Mo. A previously unreported 305 keV transition is apparent in this spectrum; it is interpreted as the direct decay from an isomeric state at $E_x = 3010$ keV. No transition from the isomer to the $I^\pi = \frac{19}{2}^-$ state was observed in this experiment. This is consistent with intensity measurements for delayed transitions below the isomer, which indicate 100% feeding through the 305 keV decay.

The spectrum shown in Fig. 2(c) illustrates promptly fed γ rays above the $E_x = 3010$ keV state, using double gates on delayed transitions (see Table I). A weak 1739 keV transition is observed in this spectrum, which fits energetically with a decay from the $E_x = 4749$ keV, $I^\pi = (\frac{31}{2}^-)$ state to the isomeric level. Table II shows Weiskopff estimates of the 1739 keV transition for different multipolarities. For this transition to compete with the collective-$E2$, 1064 keV γ ray, one would expect it to decay between states with $|I_i - I_f| = \Delta L \leqslant 2$. The 1739 keV transition is placed tentatively in the level scheme provided in Fig. 1. Other γ-ray photopeaks at 685, 764, and 842 keV are identified in this spectrum, associated with prompt transitions that possibly populate the isomeric state. Because of the complexity of the data set, particularly with γ rays of energy $E_\gamma < 1$ MeV, these transitions could not be linked confidently to the decay of specific states above the $E_x = 3010$ keV isomer in ^{99}Mo.

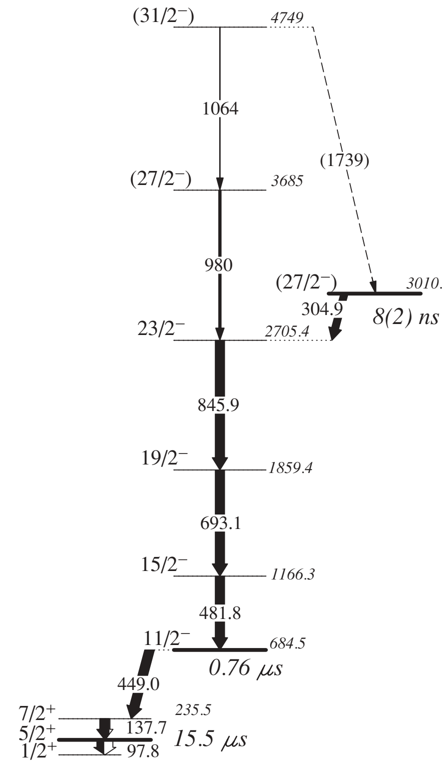

FIG. 1. Partial level scheme for transitions observed in ^{99}Mo. Arrow widths provide an indication of the relative strengths of different γ-ray decay paths. The γ-ray energies from states with $E < 3685$ keV have an error of 0.3 keV; the 980, 1064, and 1739 keV γ rays are accurate to 1 keV.

Figure 2(d) provides a γ-ray time spectrum of the double-gated delayed transitions from the isomeric $E_x = 3010$ keV state. Relative to the accelerator RF signal, the half-life of the decay is measured as $T_{1/2} = 8(2)$ ns, using a folded Gaussian plus exponential fit.

The spin-parity assignment for this previously unreported state is based on (i) the observed decay to the $I^\pi = \frac{23}{2}^-$ member of the negative-parity collective sequence in ^{99}Mo; (ii) the measured lifetime associated with the 305 keV decaying transition; and (iii) the tentatively observed 1739 keV, $\Delta L \leqslant 2$ transition that links the $E_x = 4748$ keV state with the $E_x = 3010$ keV isomer.

Weisskopf single-particle transition rates for a 305 keV transition with $E1$ or $M1$ multipolarity are $B(E1) = (1.4 \pm 0.4) \times 10^{-6}$ W.u. or $B(M1) = (9.6 \pm 2.4) \times 10^{-4}$ W.u., respectively. Such a retarded $M1$ transition is unlikely [13];

TABLE II. Weisskopf single-particle estimates for γ-ray decays in ^{99}Mo.

γ (keV)	Weiskopff estimate (s)					
	$E1$	$E2$	$E3$	$M1$	$M2$	$M3$
305	1.1×10^{-14}	7.9×10^{-9}	8.5×10^{-3}	7.8×10^{-13}	5.5×10^{-7}	5.9×10^{-1}
1152	2.1×10^{-16}	1.0×10^{-11}	7.7×10^{-7}	1.4×10^{-14}	7.1×10^{-10}	5.4×10^{-5}
1739	6.0×10^{-17}	1.3×10^{-12}	4.3×10^{-8}	4.2×10^{-15}	9.1×10^{-11}	3.0×10^{-6}

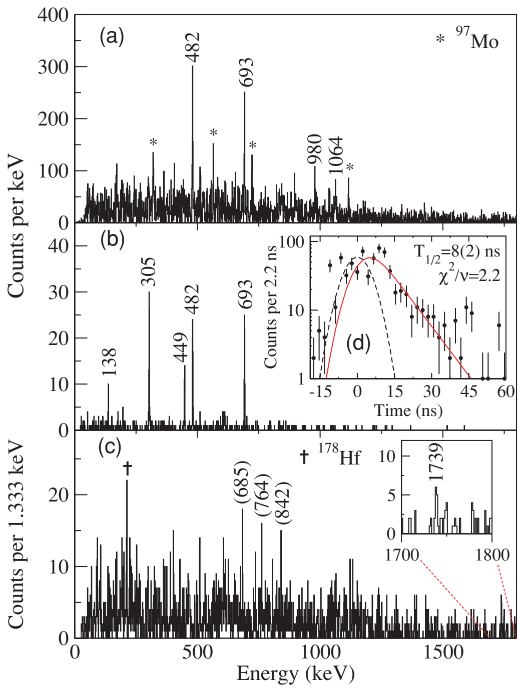

FIG. 2. (Color online) Spectra of γ-ray decays in ^{99}Mo from the short-pulsing experiment; details of the coincidence gates used to produce spectra are provided in Table I. Panels (a) and (b) show transitions associated with ^{99}Mo in prompt and delayed projections, respectively. The γ rays in (c) illustrate candidates for transitions decaying from states above the $E_x = 3010$ keV isomer. Panel (d) gives the time evolution of the isomeric decay, including a folded Gaussian plus exponential fit; the dashed line is the prompt Gaussian used in the fit (with FWHM = 12.5(10) ns), obtained from a fit to a prompt γ ray with $E_\gamma \sim 300$ keV. Contaminants (^{97}Mo and ^{178}Hf) are indicated in each spectrum where applicable.

however, Endt [13] shows that $E1$ transitions in this region can be hindered to this magnitude. Examples of such hindered $E1$ transitions can also be seen in Ref. [14]. An $E1$, 305 keV transition would imply $I^\pi = \frac{23}{2}^+$ or $\frac{25}{2}^+$ for the isomer. Under such circumstances, one might expect to observe a 1152 keV transition from the isomer to the $I^\pi = \frac{19}{2}^-$ state; Weiskopff estimates in Table II indicate that a 1152 keV, $M2$ or $E3$ transition is likely to compete with the $E1$, 305 keV decay. The fact that no competing $E_\gamma = 1152$ keV decay is observed to the $I^\pi = \frac{19}{2}^-$ (or lower spin) member of the negative-parity sequence suggests that the spin of the isomeric state is at least $I = \frac{25}{2}$.

A stretched-$E2$, 305 keV transition provides $I^\pi = \frac{27}{2}^-$ spin-parity assignment for the $E_x = 3010$ keV state, corresponding to a Weisskopf single-particle transition rate of $B(E2) = 0.96(24)$ W.u. Weiskopff estimates for the 1739 keV transition are also consistent with a $I^\pi = \frac{27}{2}^-$ assignment for the isomer. On the basis of these arguments, we suggest an $E2$ assignment for the 305 keV transition and thus a tentative $I^\pi = (\frac{27}{2}^-)$ spin-parity assignment for the isomeric state.

An $I^\pi = \frac{21}{2}^+$ isomeric state in the $N = 57$ isotope $^{105}_{48}$Cd has a reported configuration of $\nu d_{\frac{5}{2}} \otimes \pi(g_{\frac{9}{2}})^{-2}$, as deduced from the g-factor measurement in Ref. [15]. The analogous maximally aligned coupling of the $(g_{\frac{9}{2}})^2$ protons with $\nu d_{\frac{5}{2}}$, $\nu g_{\frac{7}{2}}$, and $\nu h_{\frac{11}{2}}$ would be expected to form energetically favored multiparticle states in ^{99}Mo with $I^\pi = \frac{21}{2}^+, \frac{23}{2}^+$, and $\frac{27}{2}^-$, respectively. A simple estimate for the excitation energies of such states can be made with $E_x = [\varepsilon_i + 2\Delta_p]$, assuming no residual interactions. The single-quasiparticle energy, ε_i, is taken from the low-lying single-quasiparticle states in ^{99}Mo; the proton-pair gap, $\Delta_p = 2.12$ MeV, is estimated using an empirical mass formula [16] with binding energies taken from Ref. [17]. An empirical comparison of the proton-pair gap shows that the estimate is accurate to within a few hundred keV; the excitation energy of the aligned $\nu d_{\frac{5}{2}} \otimes \pi(g_{\frac{9}{2}})^2$, $I^\pi = \frac{21}{2}^-$ state in ^{93}Mo is $E_x = 2.4$ MeV. Table III shows the energy estimates for the expected $I^\pi = \frac{21}{2}^+, \frac{23}{2}^+$, and $\frac{27}{2}^-$ states associated with the simple $(d_{\frac{5}{2}})$, $(g_{\frac{7}{2}})$, or $(h_{\frac{11}{2}})$ neutron, coupling to the maximally aligned $\pi(g_{\frac{9}{2}})^2$ configuration. The calculated state energy for the maximally aligned $\nu h_{\frac{11}{2}} \otimes \pi(g_{\frac{9}{2}})^2$ configuration appears to be within 200 keV of the observed isomeric-state energy. The experimentally suggested spin-parity for the isomer is also consistent with this assessment.

TABLE III. Multiparticle estimates for states in ^{99}Mo.

I^π	Configuration	E_x (MeV)
$\frac{27}{2}^-$	$\nu h_{\frac{11}{2}} \otimes \pi(g_{\frac{9}{2}})^2$	2.805
$\frac{23}{2}^+$	$\nu g_{\frac{7}{2}} \otimes \pi(g_{\frac{9}{2}})^2$	2.356
$\frac{21}{2}^-$	$\nu d_{\frac{5}{2}} \otimes \pi(g_{\frac{9}{2}})^2$	2.257

This interpretation assumes a spherical shape; however, preliminary potential-energy-surface calculations [18], which follow the prescription of those presented in Ref. [19], indicate a shallow oblate-triaxial minimum for the isomeric state. Whilst the spherical pairing estimate offers an impressive correlation with experimental data, a deformed shape for the isomeric state could be a possibility. In the absence of further data on the isomeric state and/or the observation of collective states associated with its configuration, it is not possible to make a firm conclusion in this respect. Nevertheless, this low-lying spherical or oblate-triaxial isomer is distinct from the prolate-triaxial structure of the $\nu h_{\frac{11}{2}}$ band, which undergoes a bandcrossing at higher spin [1] and forms a rotation-aligned $\nu h_{\frac{11}{2}} \otimes \pi(g_{\frac{9}{2}})^2$ sequence.

In summary, a previously unidentified isomeric state in ^{99}Mo has been reported here for the first time. The isomer was identified from the study of γ-ray spectroscopy in a pulsed-beam experiment. Using systematic arguments and a simple pairing estimate, the state is interpreted as a maximally aligned $\nu h_{\frac{11}{2}} \otimes \pi(g_{\frac{9}{2}})^2$ configuration.

This work is supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract DE-AC02-06CH11357 (A.N.L.); the U.S. AFOSR under Contract F49620-02-1-0187; the AWE (U.K.); and the EPSRC (U.K.).

[1] P. H. Regan, A. D. Yamamoto, F. R. Xu, C. Y. Wu, A. O. Macchiavelli, D. Cline, J. F. Smith, S. J. Freeman, J. J. Valiente-Dobón, K. Andgren, R. S. Chakrawarthy, M. Cromaz, P. Fallon, W. Gelletly, A. Gorgen, A. Hayes, H. Hua, S. D. Langdown, I.-Y. Lee, C. J. Pearson, Zs. Podolyák, R. Teng, and C. Wheldon, Phys. Rev. C **68**, 044313 (2003).
[2] A. D. Yamamoto, P. H. Regan, C. W. Beausang, F. R. Xu, M. A. Caprio, R. F. Casten, G. Gurdal, A. A. Hecht, C. Hutter, R. Krucken, S. D. Langdown, D. Meyer, J. J. Ressler, and N. V. Zamfir, Phys. Rev. C **66**, 024302 (2002).
[3] P. H. Regan, G. D. Dracoulis, G. J. Lane, P. M. Walker, S. S. Anderssen, A. P. Byrne, P. M. Davidson, T. Kibedi, A. E. Stuchbery, and K. C. Yeung, J. Phys. G **19**, L157 (1993).
[4] B. M. Nyako, J. Gizon, A. Gizon, J. Timar, L. Zolnai, A. J. Boston, D. T. Joss, E. S. Paul, A. T. Semple, N. J. O'Brien, C. M. Parry, A. V. Afanasjev, and I. Ragnarsson, Phys. Rev. C **60**, 024307 (1999).
[5] D. Jerrestam, B. Fogelberg, A. Kerek, W. Klamra, F. Liden, L. O. Norlin, J. Kownacki, D. Seweryniak, Z. Zelazny, C. Fahlander, J. Nyberg, M. Guttormsen, J. Rekstad, T. Spedstad-Tveter, A. Gizon, J. Gizon, R. Bark, G. Sletten, M. Piiparinen, Z. Preibisz, T. F. Thorsteinsen, E. Ideguchi, and S. Mitarai, Nucl. Phys. **A593**, 162 (1995).
[6] T. Ishii, A. Makishima, K. Koganemaru, Y. Saito, M. Ogawa, and M. Ishii, Z. Phys. A **347**, 41 (1993).
[7] A. J. Boston, E. S. Paul, C. J. Chiara, M. Devlin, D. B. Fossan, S. J. Freeman, D. R. LaFosse, G. J. Lane, M. Leddy, I. Y. Lee, A. O. Macchiavelli, P. J. Nolan, D. G. Sarantites, J. M. Sears, A. T. Semple, J. F. Smith, and K. Starosta, Phys. Rev. C **61**, 064305 (2000).
[8] G. A. Jones, Ph.D. thesis, University of Surrey, 2006, unpublished.
[9] I.-Y. Lee, Nucl. Phys. **A520**, 641c (1990).
[10] W. Urban, Ana Software (private communication).
[11] D. Radford, Nucl. Instrum. Methods A **361**, 297 (1995).
[12] D. Radford, Nucl. Instrum. Methods A **361**, 306 (1995).
[13] P. Endt, At. Data Nucl. Data Tables **26**, 47 (1979).
[14] W. Andrejtscheff, L. K. Kostov, H. Rotter, H. Prade, F. Stary, M. Senba, N. Tsoupas, Z. Z. Ding, and P. Raghavan, Nucl. Phys. **A437**, 167 (1985).
[15] O. Hausser, J. R. Beene, H. R. Andrews, and G. D. Sprouse, AECL-5614 **68**, 15 (1976).
[16] A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, Elmsford, NY, 1969), Vol. 1.
[17] G. Audi, A. H. Wapstra, and C. Thibault, Nucl. Phys. **A729**, 337 (2003).
[18] F. R. Xu (private communication).
[19] F. R. Xu, P. M. Walker, J. A. Sheikh, and R. Wyss, Phys. Lett. **B435**, 257 (1998).