High-spin excitations in Ru nuclei near $N=60$

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(Received 28 April 1998)

The level structures of several Ru isotopes near $A=104$ have been studied in the fission of the compound nucleus ^{197}Pb, formed in the ^{24}Mg $+^{173}$ Yb reaction at 134.5 MeV. A sequence of five transitions, observed in coincidence with known transitions in the ^{86}Sr and ^{87}Sr complementary fragments, has been assigned to ^{105}Ru. Comparison with the neighboring odd-mass Ru isotopes supports assignment of this sequence as built on the $h_{11/2}$ excitation in ^{105}Ru. The positive-parity band built on the $7/2^+$ state of ^{103}Ru has been extended above the backbending induced by the alignment of two $h_{11/2}$ neutrons. In addition, the ground-state bands of ^{104}Ru and ^{106}Ru have been extended to higher spins. [S0556-2813(98)04110-7]

PACS number(s): 23.20.Lv, 27.60.+j

I. INTRODUCTION

The nuclei near $Z\approx 40$ and $N\approx 60$ exhibit rapid changes in shape as a function of both neutron and proton numbers. For example, the ruthenium isotopes with $Z=44$ undergo a spherical to deformed transition, and possibly a transition from prolate to oblate shapes, as the number of neutrons increases from the $N=50$ closed shell. Near $N\approx 60$ large triaxial deformations ($\gamma\approx -30°$) are expected [1].

It is difficult to study Ru isotopes near $N=60$ to moderate spins because they are too close to the line of stability to be readily populated in reactions which bring in angular momentum. In contrast, the lighter, spherical isotopes can be studied following fusion-evaporation reactions and the heavier isotopes have been observed to moderate spins by prompt spectroscopy following fission of ^{248}Cm and ^{252}Cf [2,3]. Although ^{104}Ru has been studied to $\approx 14\hbar$ [4,5], little is known about higher spin states in ^{103}Ru and nothing is known about excitations built on the $\nu h_{11/2}$ configuration in ^{105,107}Ru.

In the present work excitations in several Ru isotopes near $N=60$ have been studied as fission products from a fusion reaction with compound nucleus ^{197}Pb. This method enabled the use of coincidences with transitions in the corresponding Sr isotopes, the complementary fragments, to assign transitions to ^{105}Ru. While such an identification of isotopes is easier for the even-even isotopes, it has been used to identify transitions in odd-mass nuclei, as well [6]. Moreover, comparison with known level schemes in the neighboring odd-mass Ru isotopes enabled us to assign the observed transitions in ^{105}Ru to a specific orbital. We also report on extensions of the high-spin level schemes of ^{103,104,106}Ru. Extensions of the level schemes of ^{102,104,106}Ru using the same method with a compound nucleus of ^{198}Pb were recently reported [4].

II. EXPERIMENT

The ^{197}Pb compound nucleus was formed in the ^{24}Mg $+^{173}$Yb reaction with a 134.5-MeV beam from the 88-Inch Cyclotron Facility at Lawrence Berkeley National Laboratory. The target was 1 mg/cm^2 in areal density and consisted of isotopically enriched ^{173}Yb evaporated on a 7 mg/cm^2 gold backing.

The Gammasphere array (92 Ge detectors) was used to detect γ rays. A symmetrized, three-dimensional cube was constructed to investigate coincidence relationships between the transitions. All previously known [7] Sr isotopes, from ^{84}Sr to ^{91}Sr, and Ru isotopes, from ^{99}Ru to ^{106}Ru, were identified in the present analysis. The data have also been used to study the decay of the yrast superdeformed band in ^{192}Pb [8] and the high-spin states of ^{191}Pb [9]. Additional information on the experiment and the analysis of the data are given in Ref. [9].

III. EXPERIMENTAL RESULTS

The ^{105}Ru nucleus had previously been studied via β decay of fragments following fission of actinides [10], as well as (d,p) [11] and (n,γ) [12,13] reactions. The present work is the first prompt γ-ray spectroscopy measurement of ^{105}Ru. The assignment of transitions to ^{105}Ru is based on their observation in spectra double gated on known transitions in ^{86}Sr ($6n$-fission channel) and ^{87}Sr ($5n$-fission channel), as shown in Fig. 1. Transitions from the neighboring $^{102-106}$Ru isotopes [7] are also present in these spectra originating from other fission channels. The ratios of γ-ray intensities, observed in the Sr-gated spectra in Fig. 1, for transitions in the known Ru isotopes, are summarized in Fig. 2, as well as the ratio for the strongest line assigned to ^{105}Ru, which supports the isotopic assignment. A sum of spectra double gated on the ^{105}Ru transitions is displayed in Fig. 3. Two additional transitions of 142.9 and 191.1 keV could be assigned to ^{105}Ru. While the 142.9-keV transition is similar in energy to the transition from the $3/2^+$,$5/2^+$ level at 163 keV to the first excited state at 20 keV [7], we were unable to place the 191.1-keV line, which could be involved in the decay of the $11/2^-$ state, itself possibly an isomer. The level scheme of ^{105}Ru deduced from the present work is shown in Fig. 4 and compared with partial level schemes of

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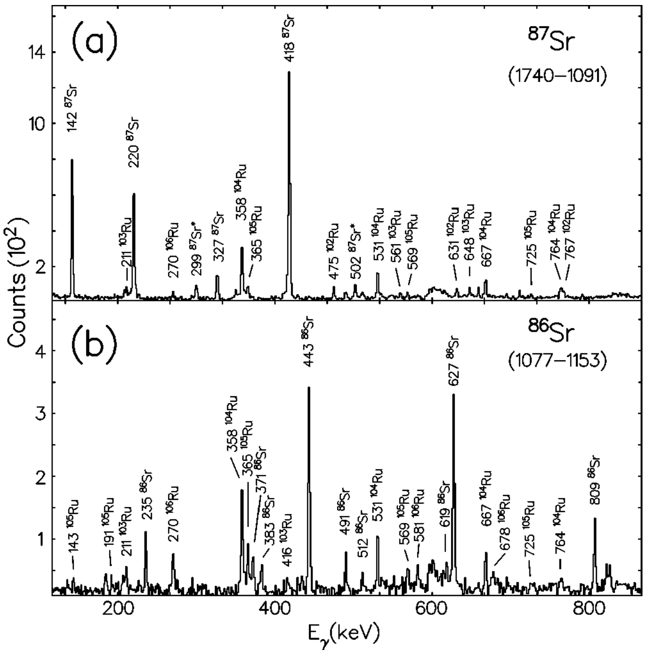

FIG. 1. Spectra obtained from double gates on the most intense transitions [7] in (a) ^{87}Sr and (b) ^{86}Sr. The energies of the transitions in keV and the isotopic assignments are given. The lines marked with an asterisk have recently been assigned to ^{87}Sr [14].

^{97,99,101,103,109,111}Ru. The relative intensities of the transitions assigned to ^{105}Ru are also displayed. The 209-keV excitation energy for the $11/2^-$ state in ^{105}Ru was determined in the earlier (d,p) measurements [11]. Spin and parity assignments of the levels of ^{105}Ru are difficult to deduce in the present measurement, because of the lack of directional correlation information for the fission products. However, the

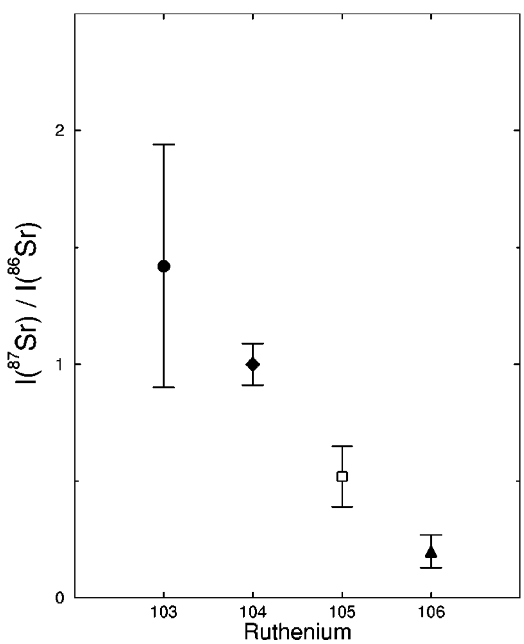

FIG. 2. Ratios of intensities for transitions in Ru isotopes observed in spectra displayed in Fig. 1. The known transitions (closed symbols) in ^{103}Ru (210.4, 415.1 keV), ^{104}Ru (357.6 keV), and ^{106}Ru (269.6 keV) were used, as well as the 365.3-keV transition proposed (open symbol) for ^{105}Ru.

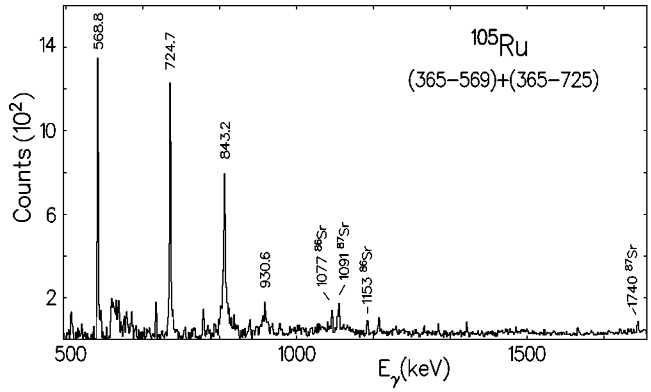

FIG. 3. Sum of spectra double gated on the 365.3- and 568.8- or 724.7-keV lines assigned to ^{105}Ru. The energies of the transitions are in keV and the assignments of the ^{86,87}Sr [7] peaks are indicated.

tentative spin assignments given in Fig. 4 are supported by a comparison with the ^{99,101,103,109,111}Ru level schemes. Hence, assuming all transitions are of $E2$ character, the highest level in ^{105}Ru observed in this work has spin 31/2 and an excitation energy of 3.6 MeV.

In the present measurement the ^{103}Ru isotope was also populated as a fission product. The sequence above the $11/2^-$ level assigned to this isotope in Ref. [18] was confirmed and a new 1004.3-keV transition was added to the top of the sequence. Our data give a slightly different energy (828.9 keV) for the $23/2^- \rightarrow 19/2^-$ transition than the 831-keV value reported in Ref. [18]. The transitions of the sequence above the $11/2^-$ level in ^{103}Ru, together with their relative intensities, are displayed in Fig. 4. Moreover, the positive-parity band in ^{103}Ru observed in Ref. [18] was extended above the backbending with the 595.8-, 782.5-, and 969.0-keV transitions, as shown in Fig. 5. All of these transitions are assumed to be stretched quadrupole in character.

Spectra obtained by double-gating on transitions of the ground-state bands of ^{104}Ru and ^{106}Ru are shown in Fig. 6. The 917.8- and 791.0-keV transitions were placed on top of the ground-state band in ^{104}Ru [4,5] and ^{106}Ru [2,4], respectively. Assuming that they are stretched $E2$ transitions, the ground-state bands are extended up to spin 16^+ and 14^+, respectively.

IV. DISCUSSION

The excitations built on the $11/2^-$ states in the odd-mass Ru isotopes are summarized in Fig. 4. The assignment to an $11/2^-$ bandhead for the dominant transitions in ^{105}Ru is based on energy ratio systematics in the lighter isotopes, as well as similarity to the sequences assigned above the $11/2^-$ states in ^{109,111}Ru [3]. The assignment of the $h_{11/2}$ neutron configuration is based on (d,p) measurements [11]. The decrease in excitation energy of the $11/2^-$ states in the heavier odd-mass Ru isotopes is expected, since the $h_{11/2}$ neutron orbital approaches the Fermi surface as the number of neutrons above the $N=50$ shell closure increases.

The energy ratio systematics for the yrast levels in even-A and $h_{11/2}$ cascades in odd-A Ru isotopes are summarized in Fig. 7. The even-A isotopes show a regular increase in these ratios as the neutron number increases, reaching a maximum

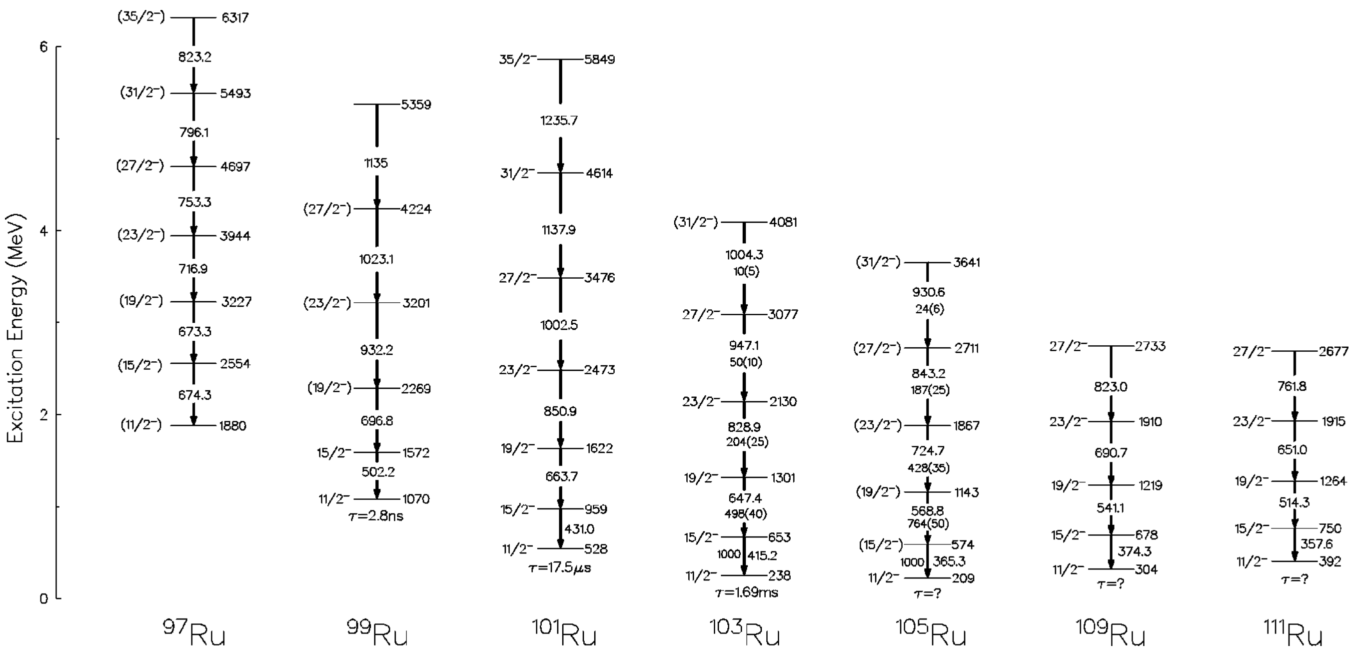

FIG. 4. Level schemes assigned to ^{103}Ru and ^{105}Ru in the present work, together with partial level schemes in the lighter ^{97}Ru [15], ^{99}Ru [16], and ^{101}Ru [17] and the heavier ^{109,111}Ru [3] nuclei. The level scheme of ^{103}Ru is partial; the positive-parity states are displayed in Fig. 5. Transition and excitation energies are given in keV, with errors in the case of ^{103,105}Ru from 0.2 to 0.6 keV. The intensities of the transitions of ^{103,105}Ru are also included, relative to the intensities of the 415.2- and 365.3-keV transitions, respectively. The known lifetimes of the $11/2^-$ levels are also shown [7].

at $N=66$, the middle of the neutron shell. In contrast, the equivalent ratios are essentially constant for the $N>54$ $h_{11/2}$ bands, with ratio values ≈ 2.5, as expected for γ-unstable or triaxial rotors. The band structures built on the $h_{11/2}$ orbital in ^{109,111}Ru have been well-reproduced in neutron coupled to triaxial rotor calculations [3] assuming constant deformations consistent with core observables and asymmetry values of $\gamma \approx 23°$.

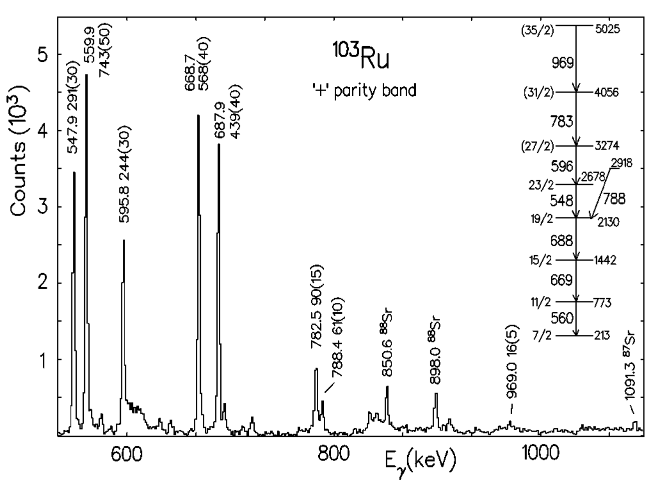

FIG. 5. Spectrum of transitions in the positive-parity band of ^{103}Ru from the sum of spectra from five double gates: the 210.6-keV transition [7], which deexcites the $7/2^+$ state, and the 560-, 669-, 688-, 548- or 595.8-keV transitions in the band. The energies of the transitions are in keV and the ^{86,87}Sr [7] peaks are indicated. The intensities of the ^{103}Ru lines relative to the 210.6-keV transition are given after the γ-ray energies. The deduced level scheme is displayed as an inset. The levels up to spin 23/2 were previously reported in Ref. [18].

The alignment of the positive-parity band of ^{103}Ru is displayed in Fig. 8(a) where it is compared with the alignments of the yrast bands in ^{102,104,106}Ru. The maximum alignment of this band in ^{103}Ru above the backbend is $\approx 11\hbar$, a gain in

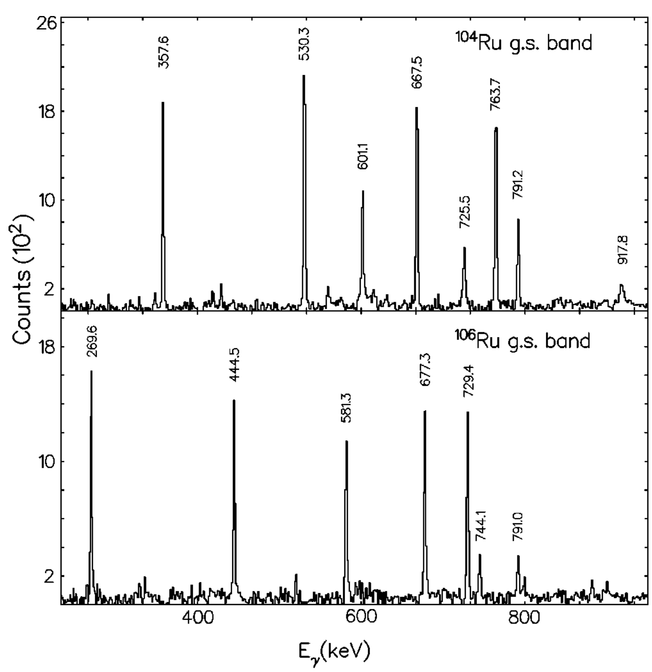

FIG. 6. Spectra obtained from double gates on transitions in (a) ^{104}Ru [4,5] and (b) ^{106}Ru [2,4]. The energies of the transitions are given in keV. (a) Sum of the double-gate combinations (601.1 +791.2 keV), (917.8+530.3 keV), and (357.6+725.5 keV). (b) Sum of the double-gates on the 744.1-keV transition and the 269.6-, 444.5-, 581.3-, or 677.3-keV transitions and the 791.0-keV transition and the 269.6-, 444.5-, or 581.3-keV transitions.

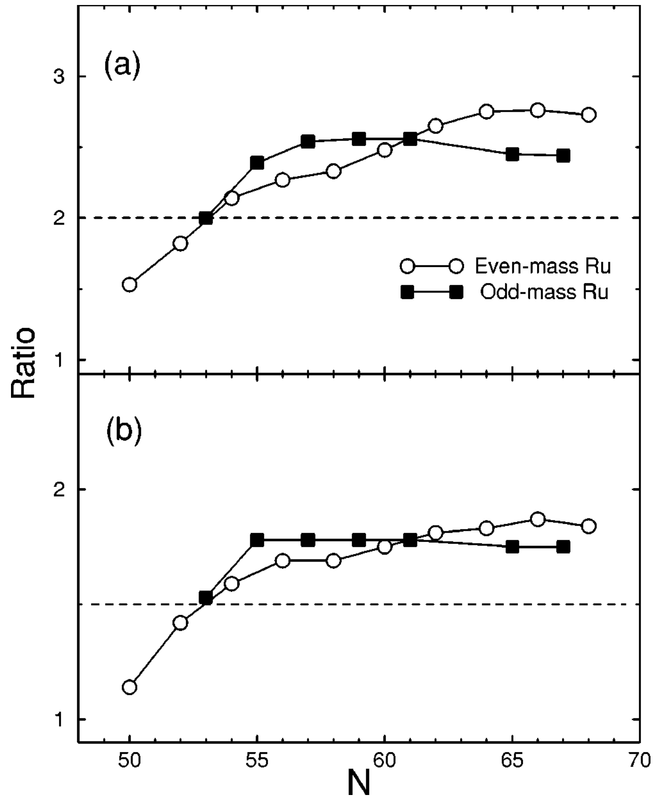

FIG. 7. Yrast energy ratios in Ru isotopes as a function of neutron number. (a) $E(4^+)/E(2^+)$ values in even-A isotopes and $E(19/2^- - 11/2^-)/E(15/2^- - 11/2^-)$ values in odd-A isotopes. (b) $E(6^+)/E(4^+)$ ratios in even-A and $E(23/2^- - 11/2^-)/E(19/2^- - 11/2^-)$ ratios in odd-A isotopes. The dotted lines are the values expected for a harmonic vibrator. Data taken from [2–5,9,15] and the present work.

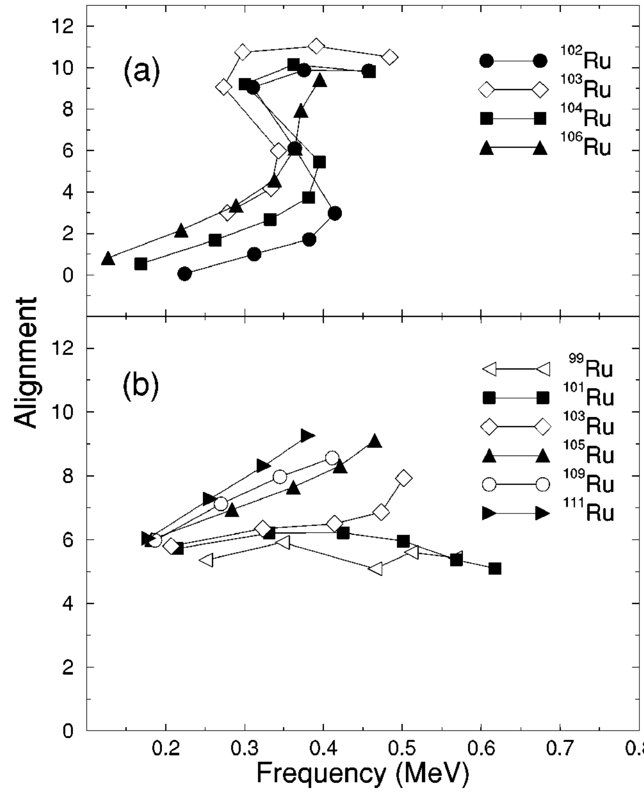

FIG. 8. Alignment in units of $\hbar$ as a function of rotational frequency in MeV for bands in Ru isotopes. (a) Positive-parity band in ^{103}Ru (open symbols) compared to yrast bands in ^{102,104,106}Ru (closed symbols). (b) $11/2^-$ bands in ^{99,101,103,105,109,111}Ru. The parameters used for the collective reference are $\mathfrak{I}_0 = 4\hbar^2/\mathrm{MeV}$ and $\mathfrak{I}_1 = 40\hbar^2/\mathrm{MeV}^3$ [5]. Data taken from Refs. [2–5,9,19,20] and the present work.

alignment consistent with the alignment of a pair of $h_{11/2}$ neutrons, but larger than the alignment of a pair of $g_{9/2}$ protons. The crossing frequency of 0.31 MeV is slightly smaller than the value in the even-A adjacent isotopes, but is consistent with the crossing frequency expected from cranked shell model calculations [5] for the alignment of two $h_{11/2}$ neutrons.

The alignments of the $h_{11/2}$ bands in ^{99,101,103,105,109,111}Ru are displayed in Fig. 8(b). All of these bands have essentially the same alignment near their bandhead, but the different slopes in the curves, especially for the heavier isotopes, result in different values at higher angular frequences. However, the different slopes of the alignments could be an artifact, because the same Harris parameters for the moments of inertia ($\mathfrak{I}_0 = 4\hbar^2/\mathrm{MeV}$ and $\mathfrak{I}_1 = 40\hbar^2/\mathrm{MeV}^3$) were used to calculate the alignments for all of these nuclei. These parameters were used in Ref. [5] to calculate the alignments for $N \approx 60$ isotopes of Mo, Ru, and Pd. A larger $\mathfrak{I}_1$ value for the heavier isotopes could be appropriate, because of an increase in collectivity that characterizes $N > 60$ nuclei in this region.

In ^{97}Ru [15] the sequence of levels built on the $11/2^-$ state is vibrational in character, indicated by the ratio values for this isotope displayed in Fig. 7, as well as the essentially equal γ-ray energies summarized in Fig. 4. In the $N = 51$ ^{95}Ru [21], the γ-ray cascade is $M1$ in character, quite different from the structures observed near $N \approx 60$. No data exist on this $h_{11/2}$ configuration in ^{107}Ru, because this nucleus is probably too light to be readily identified in prompt spectroscopy following fission of actinides and is too heavy to be observed in our present study of the fission of a ^{197}Pb compound nucleus.

V. SUMMARY

In conclusion, we have assigned transitions to ^{105}Ru based on coincidences with known transitions in ^{86}Sr and ^{87}Sr, produced as fission products in a fusion-evaporation reaction, and have established the band built on the $h_{11/2}$ neutron in ^{105}Ru. This is the first observation of γ rays in ^{105}Ru via prompt γ-ray spectroscopy and has enabled a study of moderate- to high-spin excitations in this nucleus near the valley of beta stability. Similar bands have previously been observed in the lighter ^{99,101,103}Ru isotopes, as well as ^{109,111}Ru, and can be understood as the coupling of the $h_{11/2}$ neutron to a triaxial core. The positive-parity band previously reported in ^{103}Ru has been extended above the backbending induced by the alignment of a pair of $h_{11/2}$ neutrons, and the yrast bands of ^{104}Ru and ^{106}Ru have been extended to higher excitations.

This work is an example of how the study of fragments following the fission of compound nuclei produced in fusion reactions with heavy ions can provide a wealth of information on moderate- to high-spin excitations in nuclei near the valley of beta stability. Such excitations have been previously inaccessible because of the lack of suitable reactions which could populate high-spin states in these nuclei. The present results were enabled by the high resolving power of γ-ray detector arrays such as Gammasphere. Further studies of high-spin states populated in the fission of compound lead nuclei are in progress [14,22].

ACKNOWLEDGMENTS

This work has been supported in part by the National Science Foundation (Rutgers) and the U.S. Department of Energy, under Contract Nos. W-7405-ENG-48 (LLNL) and AC03-76SF00098 (LBNL).

[1] J. Skalski, S. Mizutori, and W. Nazarewicz, Nucl. Phys. **A617**, 282 (1997).
[2] J. L. Durrell, in *Proceedings of the International Conference on Spectroscopy of Heavy Nuclei*, Crete, 1989, edited by J. F. Sharpey-Schafer and L. D. Skouras, IOP Conf. Proc. No. 105 (Institute of Physics, London, 1990), p. 307.
[3] K. Butler-Moore *et al.*, Phys. Rev. C **52**, 1339 (1995).
[4] M.-G. Porquet *et al.*, Acta Phys. Pol. B **27**, 179 (1996).
[5] P. H. Regan *et al.*, Phys. Rev. C **55**, 2305 (1997).
[6] M. A. C. Hotchkis *et al.*, Nucl. Phys. **A530**, 111 (1991).
[7] R. B. Firestone, V. S. Shirley, C. M. Baglin, S. Y. Frank Chu, and J. Zipkin, *Table of Isotopes* (Wiley, New York, 1996), and references therein.
[8] D. P. McNabb *et al.*, Phys. Rev. C **56**, 2474 (1997).
[9] N. Fotiades *et al.*, Phys. Rev. C **57**, 1624 (1998).
[10] K. Summerer, N. Kaffrell, and N. Trautmann, Z. Phys. A **273**, 77 (1975).
[11] P. Maier-Komor, P. Glassel, E. Huenges, H. Rosler, H. J. Scheerer, H. K. Vonach, and H. Baier, Z. Phys. A **278**, 327 (1976).
[12] H. H. Guven, B. Kardon, and H. Seyfarth, Z. Phys. A **287**, 271 (1978).
[13] B. Hrastnik, H. Seyfarth, A. M. Hassan, W. Delang, and P. Gottel, Nucl. Phys. **A219**, 381 (1974).
[14] N. Fotiades *et al.* (unpublished).
[15] B. Kharraja *et al.*, Phys. Rev. C **57**, 83 (1998).
[16] E. H. du Marchie van Voorthuysen, M. J. A. De Voigt, N. Blasi, and J. F. W. Jansen, Nucl. Phys. **A355**, 93 (1981).
[17] W. Klamra, K. Fransson, B. Sundström, M. Brenner, S. Engman, and R. Kvarnström, Nucl. Phys. **A376**, 463 (1982).
[18] D. R. Haenni, H. Dejbakhsh, R. P. Schmitt, and G. Mouchaty, Phys. Rev. C **33**, 1543 (1986).
[19] A. D. Efimov, M. F. Kudoyarov, A. S. Li, A. A. Pasternak, I. Adam, M. Honusek, and A. Spalek, Phys. At. Nucl. **58**, 1 (1995).
[20] H. Dejbakhsh and S. Bouttchenko, Phys. Rev. C **52**, 1810 (1995).
[21] P. Chowdhury, B. A. Brown, U. Garg, R. D. McKeown, T. P. Sjoreen, and D. B. Fossan, Phys. Rev. C **32**, 1238 (1985).
[22] N. Fotiades *et al.*, Bull. Am. Phys. Soc. **43**, 1173 (1998).