High-spin states in ^{103,105}Mo, ^{103}Nb, and the $\nu h_{11/2}$ alignment

H. Hua, C. Y. Wu, D. Cline, A. B. Hayes, and R. Teng
Nuclear Structure Research Laboratory, Department of Physics, University of Rochester, Rochester, New York 14627

R. M. Clark, P. Fallon, A. O. Macchiavelli, and K. Vetter
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720

(Received 4 March 2002; published 20 June 2002)

High-spin states in neutron-rich nuclei ^{103,105}Mo, ^{103}Nb have been studied using the ^{238}U(α,f) fusion-fission reaction. The deexcitation γ rays were detected by Gammasphere in coincidence with the detection of both fission fragments by the Rochester 4π heavy-ion detector array, CHICO. The measured fission kinematics were used to deduce the masses and velocity vectors for both fission fragments. This allowed Doppler-shift corrections to be applied to the observed γ rays on an event-by-event basis and the origin of γ rays from either fission fragment to be established. With such advantages, the yrast sequences for these nuclei have been extended to the band crossing region. This band crossing is ascribed to the alignment of a pair of $h_{11/2}$ neutrons, which is supported by the observed blocking effect for the $\nu h_{11/2}$ band in ^{105}Mo while there is no evidence for blocking in the alignment measured for either the $\nu d_{5/2}$ band in ^{103}Mo or the $\pi g_{9/2}$ band in ^{103}Nb. The observed upbend, rather than the sharp backbend seen in the Ru-Pd region, indicates a strong interaction between the ground-state and the aligned $h_{11/2}$ bands.

DOI: 10.1103/PhysRevC.65.064325 PACS number(s): 23.20.Lv, 25.70.Jj, 27.60.+j

It is known that a gradual shape transition from spherical to deformed occurs for the Mo isotopes going from the stable to the unstable neutron-rich nuclei. Considerable quadrupole deformation for the unstable neutron-rich Mo isotopes with $A>100$ has been deduced from the measured lifetimes of the first excited states [1]. The identification of the prompt γ rays from fission fragments produced by fission still is the main avenue to study the nuclear structure of such neutron-rich nuclei. Hundreds of nuclear species are populated in a typical fission process making the study of any individual nucleus difficult without an adequate resolving power to distinguish between the deexcitation γ rays from the many fission fragment species. Despite the slow progress since the first such measurement was made using spontaneous fission of ^{252}Cf [2], many interesting phenomena have been identified, such as a new region of permanent quadrupole deformation near $A=100$ nuclei [3] and a new region of stable octupole deformation in $N=88$ nuclei [4,5]. Significant progress in the understanding of nuclear structure for neutron-rich nuclei was not made until the advent of the modern γ-ray arrays that provide the necessary improvement in the resolving power to exploit nuclear fission [6,7]. One distinct result from such study of the neutron-rich Mo isotopes, produced by spontaneous fission, is the evidence of the emerging γ degree of freedom, which is manifested by the observation of the harmonic two-phonon γ-vibrational motion [8,9] and a spin-dependent triaxial deformation [10]. The richness of structure phenomena in Mo isotopes makes it a fertile ground for further nuclear structure studies.

Most recent studies of the neutron-rich Mo isotopes, performed using modern γ-ray arrays, employed spontaneous fission sources, either ^{248}Cm or ^{252}Cf, on thick backings to stop the recoiling fission fragments. The advantage of this method is that the Doppler broadening is absent if the recoiling fission fragments stop before emitting deexcitation γ rays. However, this advantage turns to a disadvantage for γ-ray transitions with lifetimes shorter than, or comparable to, the stopping times for recoiling fission fragments. Then the sharp γ-ray peak becomes a Doppler-broadened bump that dissolves into the background. This short lifetime limit happens for the collective states in neutron-rich Mo isotopes with spin beyond 10^+ or 12^+ as a result of large quadrupole deformation. Consequently, there has been little prior progress towards the study of high-spin states in these nuclei. In this paper, we address a novel technique that not only removes the restriction on the lifetimes of excited states, but also identifies the origin of γ rays from either fragment. Second, by extending the spectroscopic study to high-spin states, it presents the opportunity to study the interplay between the single-particle and collective degrees of freedom, such as the band crossing and backbending phenomena in the well-deformed, neutron-rich nuclei populated by fission.

These goals can be achieved by using a thin target, which allows the detection of both fission fragments in coincidence with the detection of the deexcitation γ rays. From the measured fission kinematics, masses and velocity vectors for both fission fragments can be derived. Appropriate Doppler-shift corrections can then be applied to the observed γ rays on an event-by-event basis and the origin of γ rays from either fission fragment can be established. Therefore, this thin-target method provides mass selectivity, identification of the fragment emitting individual γ rays, and allows the study of γ-ray transitions with short lifetimes. These advantages were demonstrated in our early works [11,12], where the ground-state band of ^{104}Mo was extended from spin 14^+ at 4.114 MeV to 20^+ at 7.282 MeV and the γ band from spin 10^+ at 3.004 MeV to spin 16^+ at 5.591 MeV.

Here, we report a study of high-spin states in the odd-A nuclei adjacent to ^{104}Mo using the thin-target technique. In the present work, the level schemes of ^{103,105}Mo have been extended substantially both in spin and excitation energy compared to the early thick-target study [13], while a mod-

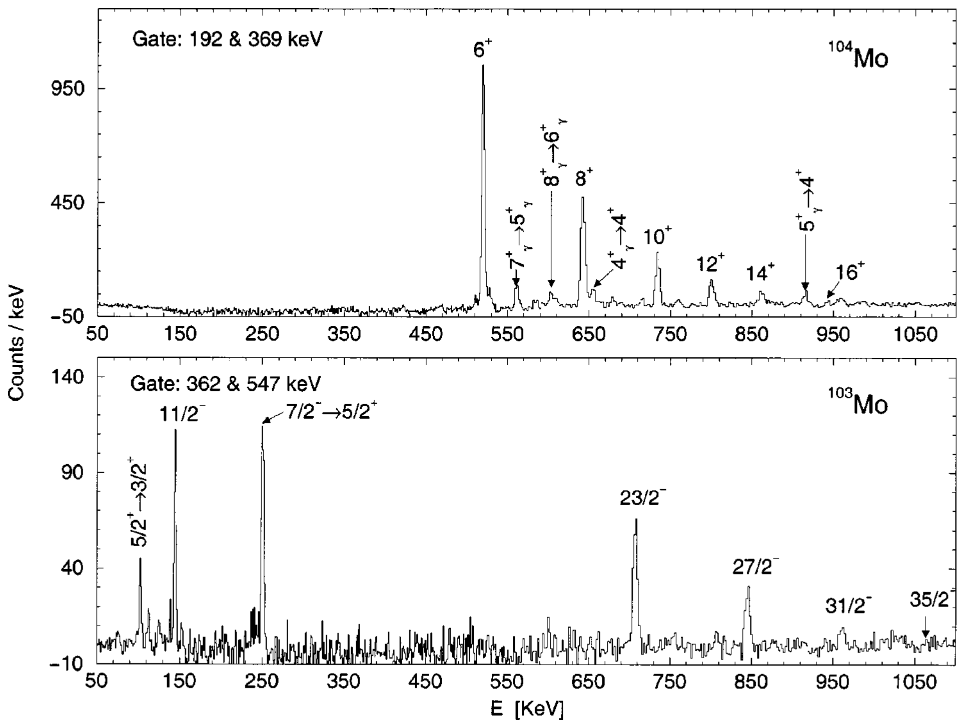

FIG. 1. Doppler-shift corrected spectra with gates on the mass and known γ-ray transitions in ^{103}Mo (lower) and ^{104}Mo (upper). The labeled transitions are $\Delta I = 2$ transitions unless specified otherwise explicitly. The uneven background observed in the upper spectrum for energy between 50 and 450 keV is due to the existence of broad γ-ray peaks from the partner nuclei, which have wrong Doppler-shift corrections.

erate extension has been made for ^{103}Nb [14]. From these data, the single-particle configuration, responsible for the observed upbend in Mo isotopes, is identified.

The present experiment was performed at the 88-Inch Cyclotron facility of Lawrence Berkeley National Laboratory by bombarding a ^{238}U target with an α beam at $E_{lab} = 30$ MeV. Neutron-rich Mo isotopes were populated from fission fragments produced by the ^{238}U(α,f) fusion-fission reaction. A 270-μg/cm^2 ^{238}U target on a ≈ 30 μg/cm^2 thickness carbon backing was used, allowing the fission fragments to recoil out of the thin target into vacuum and to be detected. The Rochester 4π, highly segmented heavy-ion detector array, CHICO [15], was used to detect the fission fragments in coincidence with the detection of the deexcitation γ rays using Gammasphere. CHICO is an ideal detector for such study since it is insensitive to the radiation damage, it can be tuned to be insensitive to light ions, such as α particles, and it has long-term stability under the high counting rate. This detector has a geometry coverage for scattering angles from 12° to 85° and 95° to 168° relative to the beam axis and an azimuthal angle totaling 280° out of 360°. A valid event requires the detection of both fission fragments and the detection of at least one γ ray. The fission fragment scattering angles, and their time-of-flight difference, were recorded in addition to the γ-ray energies and the coincident time. A total of ≈ 700 M p-p-γ events were collected, and of these, about 150 M events had at least three γ rays.

The masses, and velocity vectors, of the fission fragments were deduced from the measured angles of both fission fragments and their time-of-flight difference, assuming the total kinetic energy is the same as that of ^{240}Pu spontaneous fission [16]. The latter assumption, that the prompt fission originates from the Pu-like compound nucleus, was supported by the observed γ-ray cross correlation between the partner fragment pairs. The deduced masses had a mass resolution of 12 mass units, which reflects more or less the time resolution ≈ 500 ps. The achieved position resolution was $\approx 1°$ in θ and 4.6° in ϕ. The obtained resolutions are consistent with prior CHICO performance [17–20].

Events with at least three γ rays were used to develop the level schemes of Mo and Nb isotopes. Doppler-shift corrected γ-ray spectra gated by the mass and the known γ-ray transitions in ^{103,104}Mo are shown in Fig. 1, which have an energy resolution of better than 1%. Since the origin of γ rays from either fission fragment was established, after making the proper Doppler-shift correction, no γ-ray transitions from the partner Te isotopes are visible in the spectra. Partial level schemes of ^{103,105}Mo, deduced from the current work, are shown in Fig. 2, where the ground-state configurations were adopted from the early work [13,21,22] and were assigned to the $3/2^+[411]$ and $5/2^-[532]$ Nilsson orbits, respectively. For ^{103}Mo, the $3/2^+[411]$ band has been extended from spin $15/2^+$ at 1.159 MeV [13] to spin $31/2^+$ at 4.215 MeV, while the tentatively assigned $7/2^-$ band was extended from spin $19/2^-$ at 1.406 MeV [13] to spin $35/2^-$ at 4.983 MeV. For ^{105}Mo, the $5/2^-[532]$ band has been extended from spin $19/2^-$ at 1.353 MeV [13] to spin $39/2^-$ at 6.075 MeV. For ^{103}Nb, there are three known collective bands built on the single-proton configurations, which tentatively are assigned to the $5/2^+[422]$, $5/2^-[303]$, and $3/2^-[301]$ Nilsson orbits, respectively [14]. The ground-state $5/2^+[422]$ band has been extended from spin $25/2^+$ at 2.722 MeV to spin $29/2^+$ at 3.540 MeV. These together with members of the $5/2^-[303]$ and $3/2^-[301]$ bands are shown in Fig. 3.

The band crossing phenomenon in nuclei is illustrated by plotting the behavior of the moment of inertia vs the rotational frequency of the yrast sequence. Such plots for the

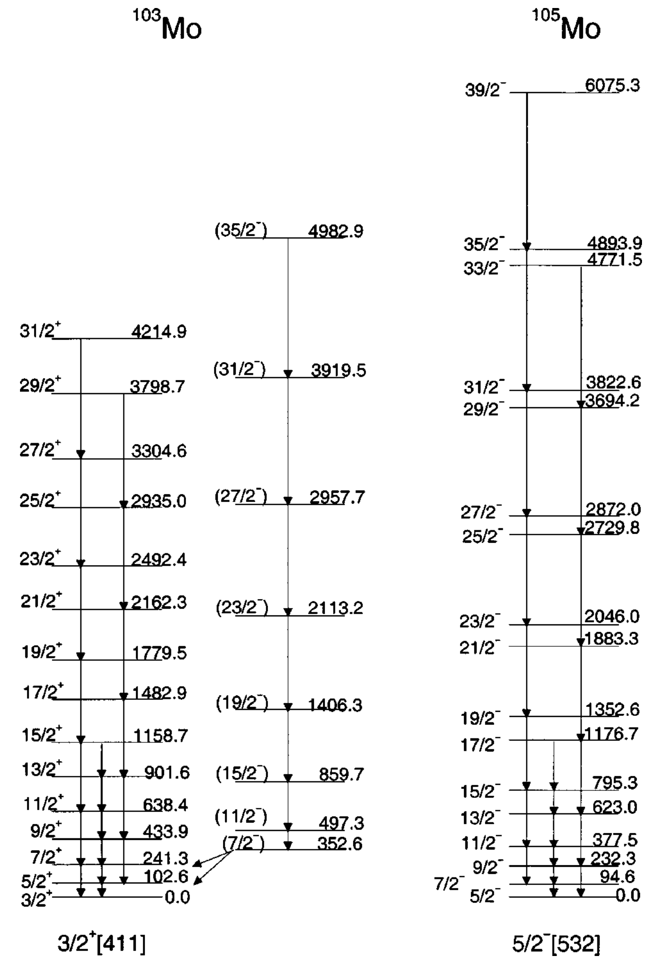

FIG. 2. Partial level schemes for the $3/2^{+}[411]$ and $7/2^{-}$ bands in^{103}Mo and the $5/2^{+}[532]$ band in ^{105}Mo.

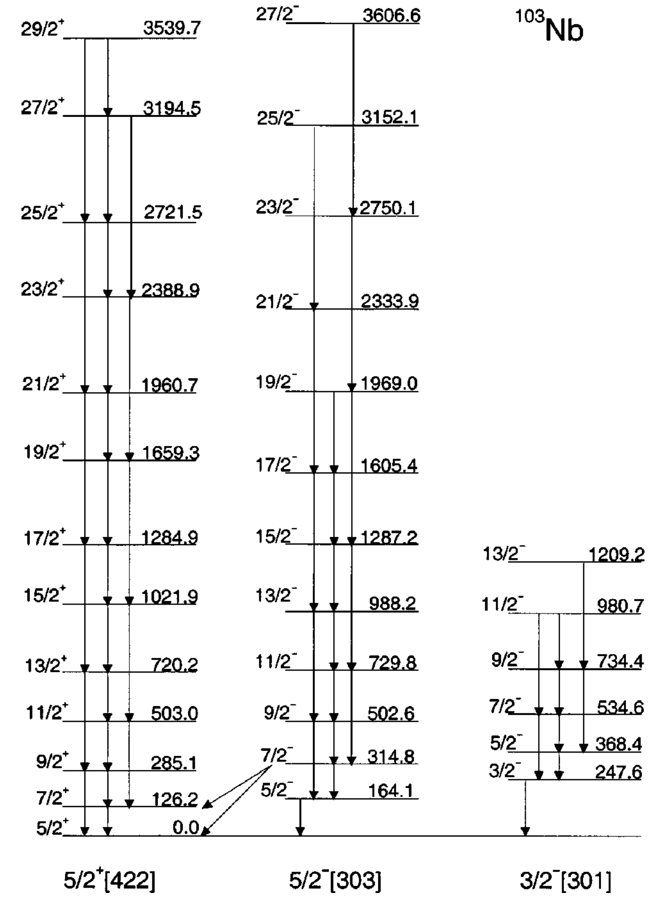

FIG. 3. Partial level schemes for the $5/2^{+}[422]$, $5/2^{-}[303]$, and $3/2^{-}[301]$ bands in ^{103}Nb.

$3/2^{+}[411]$ band of ^{103}Mo and the $5/2^{-}[532]$ band of^{105}Mo, together with that for the yrast states of^{104}Mo, are shown in Fig. 4. For both ^{103}Mo and ^{104}Mo, the moment of inertia shows a rapid increase as the rotational frequency increases and reaches a plateau at frequency ≈ 0.40 MeV. In contrast, the moment of inertia is rather flat vs the rotational frequency for the $5/2^{-}[532]$ band in ^{105}Mo, consistent with the presence of blocking. The rapid alignment process observed for the $d_{5/2}$ configuration in ^{103}Mo, coupled with the blocking effect observed for the $h_{11/2}$ configuration in ^{105}Mo, suggests that the band crossing in ^{103,104}Mo is caused by the alignment of a pair of $h_{11/2}$ neutrons. This is further supported by the gain of spin alignment $\approx 10\ \hbar$ for ^{104}Mo assuming the Harris parameters $J_0 = 3\ \hbar^2/\mathrm{MeV}$ and $J_1 = 45\ \hbar^4/\mathrm{MeV}^3$. The rapid change in the moment of inertia as a function of the rotational frequency also indicates a strong interaction between the ground-state band and the aligned $h_{11/2}$ band.

The scenario of the aligned $\nu h_{11/2}$ orbits causing the band crossing in the neutron-rich Mo isotopes can be tested further by examining the band structure based on single-proton configurations. The level scheme of ^{103}Nb, an adjacent nucleus to ^{104}Mo, is shown in Fig. 3 and the moment of inertia vs the rotational frequency for the ground-state $5/2^{+}[422]$ band is shown in Fig. 4. A rapid change in the moment of inertia similar to that of ^{103}Mo suggests that the observed rotational alignment also happens to the $\pi g_{9/2}$ configuration in ^{103}Nb. Evidence that the observed alignment of the $5/2^{+}[422]$ band in ^{103}Nb can be attributed to the $\nu h_{11/2}$ configuration is demonstrated by the measured g factor. Figure 5 shows the ratios of $|(g_K - g_R)/Q_0|$, where g_K and g_R are the g factors for the intrinsic and rotational motions and Q_0 is the intrinsic quadrupole moment, plotted as a function of spin for ^{103}Nb. These ratios were obtained using the γ-ray intensity ratios between the $\Delta I = 1$ and $\Delta I = 2$ transitions assuming that $\Delta I = 1$ transitions are pure $M1$ and that both $E2$ and $M1$ matrix elements follow the rotational relationship. The $E2$ contribution accounts for no more than 4% of the observed intensities for the $\Delta I = 1$ transitions using the measured quadrupole moment [23], which is much smaller than the quoted errors and thus is ignored in the determination of g factors. The determination for the low-spin states is not made because of the timing problem associated to low-energy γ rays detected by Gammasphere. The resulting efficiency loss due to the coincident gate with particles is difficult to recover. The current values agree reasonably with those of Ref. [13], which are shown in Fig. 5. By combining both sets of data, the gradual decrease of $|(g_K - g_R)/Q_0|$ toward the pure $\nu h_{11/2}$ configuration value [22] with increasing spin indicates that the wave functions for the high-spin states contain a significant two-

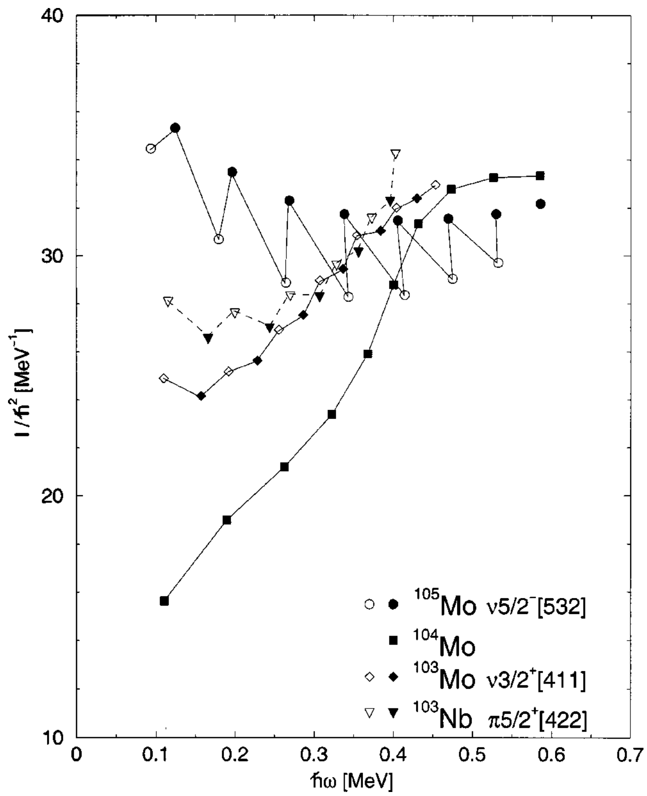

FIG. 4. The kinematical moment of inertia as a function of the rotational frequency for the $3/2^+[411]$ band in ^{103}Mo, $5/2^-[532]$ band in ^{105}Mo, ground-state band in^{104}Mo, and $5/2^+[422]$ band in ^{103}Nb. The convention used in calculating the moment of inertia and rotational frequency is from Ref. [24].

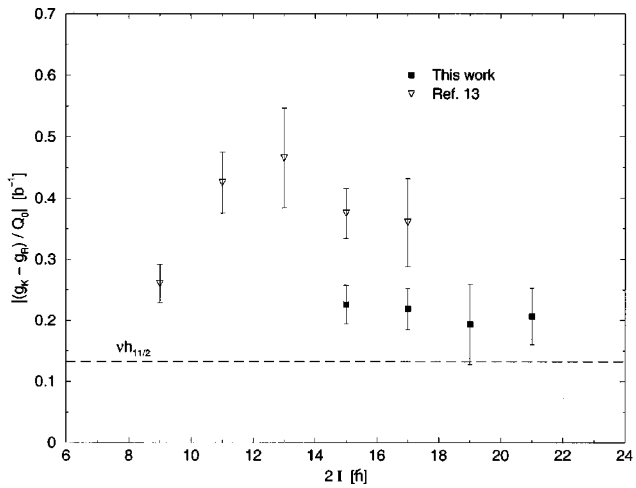

FIG. 5. Ratios of $|(g_K - g_R)/Q_0|$ for the $5/2^+[422]$ band in ^{103}Nb are plotted as a function of spin. The dashed line is the value from the transitions of the $\nu h_{11/2}$ band in^{105}Mo [22].

quasiparticle component with the $\nu h_{11/2}$ configuration. It also provides supporting evidence for a strong interaction between the ground-state and the aligned $h_{11/2}$ bands.

In summary, high-spin states for the odd-A nuclei adjacent to^{104}Mo have been studied using the ^{238}U(α,f) fusion-fission reaction. The resolving power provided by Gammasphere plus CHICO allowed use of the thin-target technique to make the proper Doppler-shift corrections to the deexcitation γ rays observed in coincidence with the detection of both fission fragments. This technique not only establishes the identities of γ rays, but also removes the difficulty in studying γ-ray transitions for states with short lifetimes. The newly acquired knowledge for the high-spin states of these odd-A neutron-rich nuclei makes it possible to identify the quasiparticle configuration responsible for the observed band crossing in ^{104}Mo. The blocking effect seen for the $\nu h_{11/2}$ band in ^{105}Mo, and the increase in alignment seen for both the $\nu d_{5/2}$ band in ^{103}Mo, and the $\pi g_{9/2}$ band in ^{103}Nb, suggests that the rotational aligned $\nu h_{11/2}$ orbit is causing the band crossing in ^{104}Mo. A strong interaction between the intersecting bands is indicated by the observed upbend in the plot for the moment of inertia vs the rotational frequency and the measured g factor for the $5/2^+[422]$ band in ^{103}Nb.

The work by the Rochester group was funded by the National Science Foundation. The work at LBNL was performed under the auspices of the Department of Energy under Contract No. DE-AC03-76SF00098.

[1] S. Raman, C.H. Malarkey, W.T. Milner, C.W. Nestor, Jr., and P.H. Stelson, At. Data Nucl. Data Tables **36**, 1 (1987), and references therein.
[2] H.R. Bowman, S.G. Thompson, and J.O. Rasmussen, Phys. Rev. Lett. **12**, 195 (1964).
[3] E. Cheifetz, R.C. Jared, S.G. Thompson, and J.B. Wilhelmy, Phys. Rev. Lett. **25**, 38 (1970).
[4] W.R. Phillips, I. Ahmad, H. Emling, R.V.F. Janssens, T.L. Khoo, and M.W. Drigert, Phys. Rev. Lett. **57**, 3257 (1986).
[5] W.R. Phillips, R.V.F. Janssens, I. Ahmad, H. Emling, T.L. Khoo, and M.W. Drigert, Phys. Lett. B **212**, 402 (1988).
[6] A. Ahmad and W. Phillips, Rep. Prog. Phys. **58**, 1415 (1995).
[7] J. Hamilton *et al.*, Prog. Part. Nucl. Phys. **35**, 635 (1995).
[8] A. Guessous *et al.*, Phys. Rev. Lett. **75**, 2280 (1995).
[9] A. Guessous *et al.*, Phys. Rev. C **53**, 1191 (1996).
[10] A.G. Smith *et al.*, Phys. Rev. Lett. **77**, 1711 (1996).
[11] M.W. Simon *et al.*, in *Proceedings of the International Conference on Fission and Properties of Neutron Rich Nuclei, Sanibel Island, FL*, edited by J.H. Hamilton and A.V. Ramayya (World Scientific, Singapore, 1998), p. 270.
[12] M.W. Simon, Ph.D. thesis, University of Rochester, 1999.
[13] M.A.C. Hotchkis *et al.*, Nucl. Phys. **A530**, 111 (1991).
[14] J. Hwang *et al.*, Phys. Rev. C **58**, 3252 (1998).
[15] M.W. Simon *et al.*, Nucl. Instrum. Methods Phys. Res. A **452**, 205 (2000).
[16] J. Weber, H. Specht, E. Konecny, and D. Heunemann, Nucl. Phys. **A221**, 414 (1974).
[17] C.Y. Wu, M. Simon, D. Cline, G. Davis, A. Macchiavelli, and K. Vetter, Phys. Rev. C **57**, 3466 (1998).
[18] K. Vetter *et al.*, Phys. Rev. C **58**, 2631 (1998).

[19] C.Y. Wu *et al.*, Phys. Rev. C **61**, 021305(R) (2000).
[20] C.Y. Wu *et al.*, Phys. Rev. C **64**, 064317 (2001).
[21] M. Liang, H. Ohm, I. Ragnarsson, and K. Sistemich, Z. Phys. A **346**, 101 (1993).
[22] M. Liang, H. Ohm, B. Sutter, and K. Sistemich, Z. Phys. A **351**, 13 (1995).
[23] M. Liang, H. Ohm, B. De Sutter, and K. Sistemich, Z. Phys. A **344**, 357 (1993).
[24] M.J.A. de Voigt, J. Dudek, and Z. Szymanski, Rev. Mod. Phys. **55**, 949 (1983).