the former process and the $\vec{k}$ dependence of the scattering matrix element (for either exciton-exciton or exciton-trap scattering) favors the latter.

Finally, when we pump the exciton-phonon (e-p) state at $E_{ex}+107\ cm^{-1}$, excitons are not selectively prepared in a narrow band of $\vec{k}$ since emission is observed for excitons at $k\approx 0$ and $k\sim 0.8(\pi/c)$ in $<10^{-7}$ sec. This shows that the e-p state does not simply decay into two particles, but goes through intermediate states, probably a band of e-m states, and thereby loses phase information.

In conclusion, we have proposed a scheme of resonant optical pumping and monochromatic fluorescence detection to measure the total loss of phase memory for excitations in solids. It has been possible to show that in the very narrow $^4T_1\ e1$ exciton band in MnF_2, total phase memory is lost rather slowly. The techniques reported here may be extended to nonmagnetic crystals where a phonon would be needed to provide momentum conservation in two-particle processes.

The authors gratefully acknowledge the technical assistance of C. F. Pike and V. T. Maxson, and helpful discussions with D. M. Burland and H. Morawitz.

†Work supported in part by the U. S. Air Force Office of Scientific Research under Contract No. F44620-71-C-0081.

[1]R. E. Dietz, A. E. Meixner, and H. J. Guggenheim, J. Lumin. 1,2, 279 (1970).

[2]R. E. Dietz, A. E. Meixner, H. J. Guggenheim, and A. Misetich, Phys. Rev. Lett. 21, 1067 (1968).

[3]This occurs via spin-allowed intrasublattice scattering. Resonant optical pumping has recently been used to study intersublattice exciton scattering by J. F. Holzrichter, R. M. Macfarlane, and A. L. Schawlow, Phys. Rev. Lett. 26, 652 (1971).

[4]This is not pure $e1$-m. See R. E. Dietz, A. Misetich, and H. J. Guggenheim, Phys. Rev. Lett. 16, 841 (1966).

Backbending and Forking in the Yrast States of Even Os Isotopes*

R. A. Warner, F. M. Bernthal, J. S. Boyno, and T. L. Khoo
Cyclotron Laboratory and Departments of Chemistry and Physics, Michigan State University, East Lansing, Michigan 48823

and

G. Sletten
The Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

(Received 19 June 1973)

The yrast levels have been determined to spin 16 and 18 in $^{182,184,186}Os$ and to spin 12 in ^{188}Os from γ-ray excitation functions, anisotropies, and coincidence data from the reactions $^{182,184,186}W(\alpha,4n)$ and $^{186}W(\alpha,2n)$. A fork is observed in the ^{186}Os yrast band at spin 12. Above spin 12 the $\mathcal{I}$-versus-ω^2 curves for $^{182,184,186}Os$ display "backbending" behavior. Such behavior has not been reported for any other nuclei with more than 96 neutrons.

Dramatic departures from simple rotational spacing have been reported for the yrast levels of several even-even deformed rare-earth nuclei.[1] For most of these nuclei, the yrast levels below some critical value of angular momentum can be fitted as members of a ground-state rotational band (grb) with a moment of inertia that increases slowly with rotational frequency. Above this critical value, however, striking changes sometimes occur in the moments of inertia $\mathcal{I}$ and rotational frequencies ω computed from the level spacings. These changes are often referred to as backbending because of the shape of the curve of $\mathcal{I}$ versus ω^2.

Pairs of particles moving in a rotating deformed potential experience a Coriolis force which opposes the pairing. Two currently popular explanations of backbending are based on the effect of the Coriolis force on neutron pairs. Calculations based on the early work of Mottelson and Valatin[2] predict a coherent breakdown of pairing between neutrons at high rotational frequency—a Coriolis antipairing phase transition from a system with the superfluid moment of inertia of the ground state to a system with the larger moment of inertia of a more rigid nucleus. Stephens and Simon,[3] on the other hand, have proposed a model for yrast states above the backbending region in which only one pair of $i_{13/2}$ neutrons is broken and is at least partially decoupled from the rotating core. If this decoupled two-quasiparticle band intersects the grb with little mixing between the two bands, backbending will occur in the yrast cascade. The Coriolis interaction responsible for the decoupled band is strongest for nucleons with small angular-momentum projection on the symmetry axis, and for previously reported cases of backbending in deformed nuclei, the $i_{13/2}$ states near the Fermi surface all have small projections ($\Omega = \frac{3}{2}, \frac{5}{2}$). Even-mass Os isotopes with neutron numbers ranging from 106 through 112 were selected for the present study, because in these nuclei the corresponding $i_{13/2}$ neutron projections are significantly larger ($\Omega = \frac{9}{2}, \frac{11}{2}$), and the Coriolis matrix elements were expected to be correspondingly smaller. Other things being equal, the transition to the two-quasiparticle band formed from decoupling $i_{13/2}$ neutrons should therefore occur at higher spins in the Os isotopes.

Self-supporting foils of separated tungsten isotopes (^{182,184,186}W) were prepared with the heavy-ion sputtering[4] apparatus at the Niels Bohr Institute, and bombarded with beams of α particles from the Michigan State University sector-focused cyclotron. γ-ray spectra accompanying the (α, xn) reactions on these targets have been analyzed to establish the yrast cascades in ^{182,184,186,188}Os. Table I contains a partial list of the transitions observed. While many other transitions are seen in the spectra, this paper will be confined to a discussion of those listed in Table I.[5] The cascades indicated were established by the results of three-parameter (E_1, E_2, T_{12}) coincidence experiments performed using two Ge(Li) detectors of ~7% efficiency. In the ^{186}Os experiment more than 13 million coincidence events were accumulated, while in each of the other cases more than 5 million events were recorded.

TABLE I. Transition energies (in keV) for yrast and near-yrast cascades in four osmium isotopes.

Transition	^{182}Os	^{184}Os	^{186}Os	^{188}Os
2→ 0	127.0	119.8	137.2	155.0
4→ 2	273.4	263.8	296.8	322.9
6→ 4	393.3	390.3	434.8	462.3
8→ 6	483.0	500.7	552.1	574.5
10→ 8	533	596.2	647.4	655.1
12→10	533	675.6	713.1	685.9 [b]
14→12	493.5	712.7	658.8	···
			776.8 [a]	
16→14	479.4	528 [b]	494.8	···
18→16	···	···	559.5 [b]	···

[a]This transition feeds the 12^+ level in the yrast cascade, and displays an angular distribution and an excitation function consistent with assignment as a stretched quadrupole transition.

[b]The initial spins assigned to these transitions are less certain than are the others in the table.

The ^{182,184,186}Os states were populated by the $(\alpha, 4n)$ reaction with 48-MeV α particles. The spin assignments in these three isotopes are based on excitation-function and angular-distribution measurements. The relative γ-ray yields (at 125° with respect to the beam direction) were measured for beam energies of 41, 45, 48, and 50 MeV. At 48 MeV, measurements were also made with the detector at 90°, 135°, and 145°. The transitions for which energies are listed in the first three columns of Table I display excitation functions and angular distributions consistent with their assignments in stretched quadrupole cascades, although the multipolarities assigned to the transitions at 528 keV in ^{184}Os and at 559.5 keV in ^{186}Os are tentative.

States in ^{188}Os cannot be reached by the $(\alpha, 4n)$ reaction, but in conjunction with a study[6] of levels in ^{187}Os, four sets of coincidence data were accumulated for the reaction ^{186}W$(\alpha, 2n)^{188}$Os at α-particle energies ranging from 26 to 35 MeV. However, the angular momentum available at the lower energies was sufficient only to permit the identification of the 12^+ grb state, and the spectrum was dominated by the $(\alpha, 3n)$ reaction products at the higher energies.

The curves in Fig. 1 result from plotting

$$2\mathscr{I}/\hbar^2 \equiv \Delta(I(I+1))/\Delta E$$

against

$$\hbar^2\omega^2 \equiv \{\Delta E/\Delta([I(I+1)]^{1/2})\}^2$$

for each transition. The values of $\Delta(I(I+1))$, ΔE, and $\Delta([I(I+1)]^{1/2})$ are determined from Table I. The ^{178,180}Os curves, included for completeness, are computed from published results.[7] Attention should first be directed to the point in Fig. 1 connected by a dashed line to the other ^{186}Os points. This point is computed from the 776.8-keV transition feeding the 12^+ grb state from a *non*yrast 14^+ state. The experimental level spacing and excitation function for this transition are precisely those expected for the grb while the same measurements for the yrast $14^+ \to 12^+$ transition yield

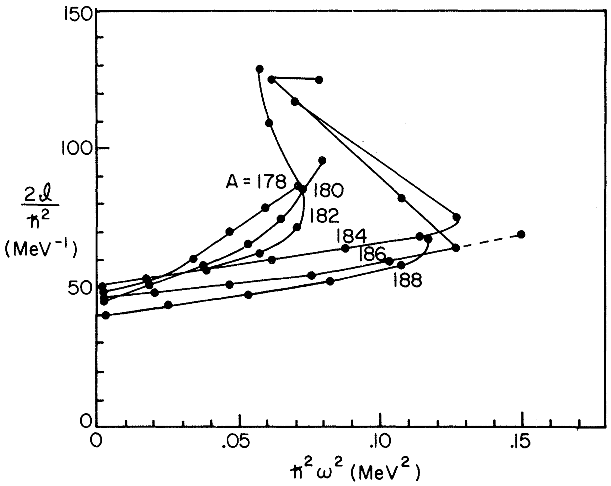

FIG. 1. Moment of inertia versus the square of rotational frequency for each yrast transition in even-mass osmium isotopes. The curve joining the data for each isotope is labeled with the mass number. The ^{178,180}Cs data are from Ref. 7. The quantities plotted are defined in the text.

quantities anomalous for the grb. Thus the yrast states above spin 12 in ^{186}Os must be members of some other band. Furthermore, this band must be relatively unmixed with the grb, as a search for the $E2$ transition from the yrast 16^+ state to the grb 14^+ state was negative. The $B(E2)$ strength of this unseen line is less than 30% of that for the branch to the yrast 14^+ state. The intrinsic structure of the band composed of yrast states above spin 12 remains undetermined.

A perfect rotor would be represented in Fig. 1 by a horizontal line. At low spin the heavier Os isotopes appear to be the best rotors, but ^{184,186}Os also display two of the most pronounced examples of backbending behavior known. At first glance, this behavior seems at odds with the explanation offered by Stephens and Simon[3] for backbending in other nuclei. However, the location of the Fermi surface among the $i_{13/2}$ neutron states is not the only factor of importance to a discussion of backbending. Coriolis matrix elements also depend on the rotational parameter $\hbar^2/2\mathscr{J}$. This parameter is significantly larger for the Os isotopes than for the more deformed rare-earth nuclei for which backbending has been reported. In addition, the large hexadecapole moments found in the Os region[8] lead to a compression of the low-Ω states, thereby enhancing the mixing between the various $i_{13/2}$ Nilsson orbitals. This mixing is documented for the $\frac{9}{2}^+$ [624] and $\frac{11}{2}^+$ [615] bands of nearby odd-neutron Hf, W, and Os isotopes.[6,9] Thus, $i_{13/2}$ neutrons may still be effectively decoupled in the even-mass Os isotopes, despite the location of the Fermi surface far from the low-Ω levels. Alternatively, Stephens *et al.*[10] have recently suggested that decoupling of $h_{9/2}$ protons, apparent in odd-mass Re data,[11] may contribute to the Os backbending. However, detailed calculations incorporating these ideas have yet to be performed.

For the moment, it is not possible to say whether the backbending reported here results from a decoupling of $i_{13/2}$ neutrons or of $h_{9/2}$ protons, or from a more coherent Coriolis antipairing phase transition. With the observation of backbending in the Os isotopes it now appears that the phenomenon occurs near the edges of the rare-earth deformed region, but perhaps not near the center.

The authors are indebted to K. Kumar and F. S. Stephens for valuable discussions.

*Work supported in part by the U.S. Atomic Energy Commission and in part by the National Science Foundation.

[1]Excellent reviews, including extensive bibliographies, have been prepared by A. Johnson and Z. Szymański [Phys. Rep. 7C, 181 (1973)] and R. Sorensen [Rev. Mod. Phys. 45, 353 (1973)].

[2]B. R. Mottelson and J. G. Valatin, Phys. Rev. Lett. 5, 511 (1960).

[3]F. S. Stephens and R. S. Simon, Nucl. Phys. A183, 257 (1972).

[4]G. Sletten and P. Knudsen, Nucl. Instrum. Methods 102, 459 (1972).

[5]The authors will publish the complete results of these studies elsewhere.

[6]J. S. Boyno, F. M. Bernthal, T. L. Khoo, and R. A. Warner, to be published.

[7]J. Burde, R. M. Diamond, and F. S. Stephens, Nucl. Phys. A92, 306 (1967).

[8]D. L. Hendrie, B. G. Harvey, J.-C. Faivre, and J. Mahoney, in Lawrence Radiation Laboratory Report No. UCRL-20426, 1970 (unpublished), p. 87; S. G. Nilsson, C. F. Tsang, A. Sobiczewski, Z. Szymański, S. Wycech, C. Gustafson, I.-L. Lamm, P. Möller, and B. Nilsson, Nucl. Phys. A131, 1 (1969).

[9]F. M. Bernthal and R. A. Warner, Michigan State University Cyclotron Laboratory Annual Report, 1971–72 (unpublished), pp. 63 ff.; Th. Lindblad, P. Kleinheinz, and H. Ryde, Research Institute for Physics, Stockholm, Annual Report, 1972 (unpublished), pp. 16 ff.

[10]F. S. Stephens, P. Kleinheinz, R. K. Sheline, and R. S. Simon, private communication.

[11]J. R. Leigh, J. O. Newton, L. A. Ellis, M. C. Evans, and M. J. Emmott, Nucl. Phys. A183, 177 (1972).