The Proton $h_{11/2}$ Intruder Orbital: Evidence for Collectivity and a Strong Proton-Neutron Interaction

V. P. Janzen,[a] H. R. Andrews, B. Haas,[b] D. C. Radford, and D. Ward
AECL Research, Chalk River Laboratories, Chalk River, Ontario, Canada K0J 1J0

A. Omar, D. Prévost, M. Sawicki, P. Unrau, and J. C. Waddington
McMaster University, Hamilton, Ontario, Canada L8S 4M1

T. E. Drake and A. Galindo-Uribarri[c]
University of Toronto, Toronto, Ontario, Canada M5S 1A7

R. Wyss[d]
Joint Institute for Heavy Ion Research, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

(Received 30 October 1992)

A rotational band based on the proton $h_{11/2}$ orbital has been observed to high spin ($\frac{79}{2}\hbar$) and high rotational frequency ($\hbar\omega \simeq 1.0$ MeV) in the nucleus ${}^{113}_{51}$Sb. The measured transition quadrupole moment is $Q_0 = 4.4 \pm 0.6\ e\,$b, consistent with an axial prolate deformation of $\beta_2 \simeq 0.32$. A large interaction strength (360 ± 60 keV) has been measured for the rotational alignment of $h_{11/2}$ neutrons which, together with a considerable delay in the crossing frequency ($\Delta\hbar\omega \simeq 0.09$ MeV), is construed as the first direct evidence of a large high-j proton-neutron interaction.

PACS numbers: 21.10.Re, 21.30.+y, 23.20.Lv, 27.60.+j

A knowledge of the forces which drive the few-body nuclear system into collective motion, together with an understanding of both collective and noncollective effects within a single unified model, are fundamental goals in the study of nuclear structure. At modest excitation energy and spin in the odd-mass antimony nuclei (Sb, $Z = 51$), collective band structures are observed to coexist side by side with states corresponding to single-particle excitations [1, 2]. The collective states have been interpreted as proton particle-hole excitations across the major shell gap, made energetically possible by the combination of strong proton-pair correlations and a postulated proton-neutron interaction (e.g., Ref. [3]). The onset of prolate deformation, and thus the appearance of collective rotational bands, has also been linked to the occupation of particular orbitals which are preferentially lowered in energy at large quadrupole deformations (e.g., Ref. [4]), and hence exert a driving force towards increased deformation. Such high-j "intruder" orbitals are characterized by large values of single-particle angular momentum aligned along the axis of rotation, leading to a further reduction in energy due to the Coriolis force at high rotational frequency.

Before this study very little experimental information existed concerning states at high spin ($I \geq 20\hbar$) in nuclei near the $Z = 50$ closed spherical shell. In addition, no lifetime data (and therefore no measure of the collectivity) existed for the known band structures. In this Letter we address the role of the proton $h_{11/2}$ orbital as a high-spin intruder configuration, and report the first measurement of a transition quadrupole moment for a collective band in the $Z = 50$ region. Moreover, we show that the observed characteristics of the $h_{11/2}$ intruder band may now be used to test the standard mean-field approach to nuclear structure calculations.

High-spin states in ^{113}Sb have been populated via the ^{94}Mo(^{23}Na,$2p2n$) reaction, with a 117-MeV sodium beam provided by the Tandem Accelerator SuperConducting Cyclotron (TASCC) Facility at Chalk River Laboratories. Experiments were performed with thin self-supporting and Au-backed enriched target foils, to provide high energy-resolution data and Doppler-shift information, respectively. Approximately 2×10^8 (self-supporting target) and 3.2×10^8 (backed target) γ-γ events were collected with the 8π spectrometer, which comprises 20 Compton-suppressed HPGe detectors and a spherical shell of 71 BGO detectors that covers nearly 95% of 4π solid angle. An event trigger required a suppressed HPGe twofold coincidence together with a K-fold coincidence in the BGO ball, where $K \geq 8$. In sorting the data to construct E_γ-E_γ coincidence matrices, BGO-ball sum-energy (H) and fold (K) thresholds of $H_{\min} = 14$ MeV and $K_{\min} = 15$ were set. Ratios of γ-ray intensities from the rings of HPGe detectors at polar angles $\pm 37°$ and $\pm 79°$ were used with the method of directional correlation of oriented states (DCO) to determine the transition multipolarities and thus the spins of excited states.

A rotational band consisting of 16 stretched quadrupole transitions was observed as shown in Fig. 1, extending to $\frac{79}{2}\hbar$ in spin, approximately 21 MeV in excitation energy and almost 1 MeV/$\hbar$ in rotational fre-

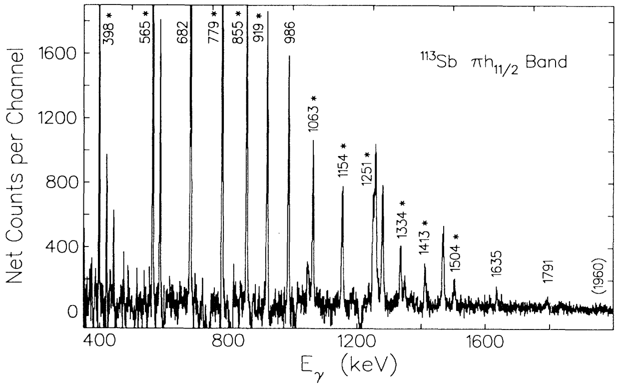

FIG. 1. Sum of γ-ray spectra gated on transitions within the proton $h_{11/2}$ band in ^{113}Sb. Peaks not labeled by their energy correspond to out-of-band decays or transitions between spherical states. Gating transitions are marked by an asterisk. Note that the most intense peaks exceed the scale.

quency ($\hbar\omega \simeq E_\gamma/2$). Figure 2 shows a partial level scheme of the nucleus obtained from the present work. The spin and parity of the $\frac{15}{2}^-$ states are fixed by the multipolarities of the transitions connecting them with the lower-lying negative-parity levels, which were already known [1]. The only negative-parity orbital close to the Fermi surface for $Z \simeq 51$ is the $K = \frac{1}{2}$ member of the $h_{11/2}$ j shell and so we have identified this band with the proton $\frac{1}{2}[550]$ Nilsson configuration. Above approximately 4 MeV in excitation energy this structure is yrast, and collects much of the γ-ray flux from the decay of high-spin states populated following particle emission.

Using the backed-target data we have performed a Doppler-shift (DSAM) analysis of the γ-ray centroid shifts observed in the $\pm 37°$ rings of HPGe detectors, to extract an average quadrupole moment for the rotational sequence. As shown in Fig. 2 (inset) the fractional shifts are best fitted by $Q_0 = 4.4 \pm 0.6$ eb, consistent with a prolate deformation $\beta_2 \simeq 0.32$ assuming axial symmetry. Both the enhanced deformation and the yrast nature of the $h_{11/2}$ band up to high spin and high rotational frequency are characteristics of high-j intruder bands in the $A \sim 130$ and $A \sim 180$ mass regions [6].

We have carried out Nilsson-Strutinsky calculations of the potential energy surfaces for ^{113}Sb, which predict the existence of an excited $h_{11/2}$ bandhead with prolate deformation $\beta_2 \simeq 0.28$. If axial symmetry is assumed, this corresponds to a quadrupole moment of 3.9 eb, in reasonable agreement with the measured value. We have also performed cranked Strutinsky calculations of total Routhian surfaces, with a Woods-Saxon potential [7]. The predicted value for the quadrupole moment of 3.8 eb is also in reasonable agreement. Thus in this case, as in many other instances, the deformed mean-field approach can describe the coexistence of spherical (single-particle) and enhanced-deformation (collective) states.

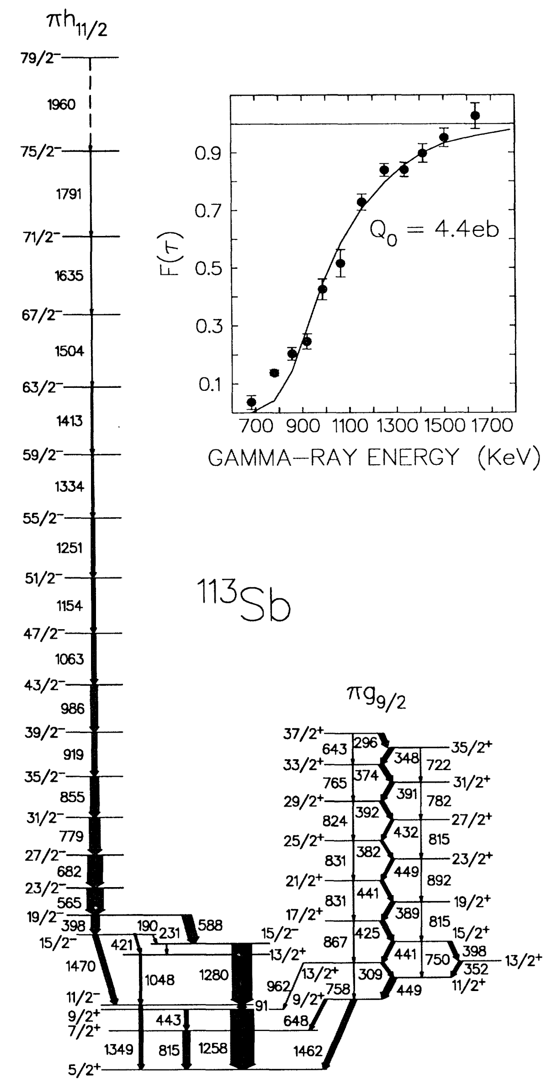

FIG. 2. Partial level scheme of ^{113}Sb obtained from the present work. The noncollective states up to spin $\simeq \frac{23}{2}\hbar$ and the proton $g_{9/2}^{-1}$ band (right-hand side of level scheme) up to spin $\frac{19}{2}\hbar$ were already known [1]. For reasons of space the noncollective states above spin $\frac{15}{2}\hbar$ have not been shown. Inset: Fraction of the full Doppler shift of γ rays in the deformed proton $h_{11/2}$ band. The calculated curve has been obtained with the prescription used in Ref. [5], assuming a constant quadrupole moment which is identical for in-band and side-feeding transitions.

The cranked shell model, which is a mean-field approach, has been successful in explaining the breaking of pairs and the changes in deformation induced by collective rotation. This success comes about partly because the mean field can take into account important nucleon-nucleon interactions. Nevertheless, a mean-field theory is clearly an approximation, subject to modification by additional residual interactions, such as those between valence neutrons and protons. We can test this by examining the properties of band crossings where the rotational alignment of neutrons takes place in the presence of an odd proton. For example, valence neutrons and protons occupy similar high-j orbitals in the light Sb nuclei. Consequently, there is a large overlap between the neutron and proton wave functions and the alignment of valence neutrons may thus be particularly influenced by an interaction between high-j neutrons and protons.

The properties of the $h_{11/2}$ band in ^{113}Sb can be described within the rotating frame of the nucleus, as shown in Fig. 3. The increases in the alignment plot and the corresponding peaks in the $\mathcal{J}^{(2)}$ moment of inertia represent two distinct band crossings, at $\hbar\omega = 0.46$ and 0.69 MeV. The first band crossing is due to the rotational alignment of a pair of $h_{11/2}$ neutrons (cf. Ref. [8]), but appears at a different frequency and with a much larger interaction than either the known neutron $h_{11/2}$ alignment in the ^{110,112,114}Sn nuclei [see Fig. 3(b)] or the predicted crossing. A similar pattern has been observed in high-j intruder bands in other mass regions and has been linked to the presence of a residual proton-neutron interaction [9], but in those cases, a measurement of the interaction strength was not possible.

From Fig. 3(a) the gain in aligned angular momentum due to the rotational alignment of valence nucleons is estimated to be $7.5\hbar$ at the first crossing and $4.5\hbar$ for the second crossing. With the assumption of a constant moment of inertia for the underlying core, and of an interaction which is spin and frequency independent, the

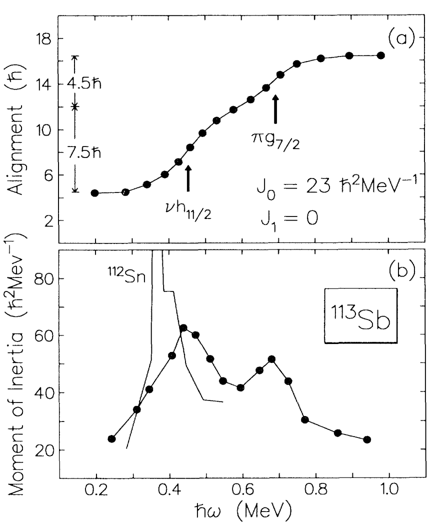

FIG. 3. (a) Quasiparticle aligned spin i, and (b) dynamic moment of inertia $\mathcal{J}^{(2)}$ as a function of rotational frequency, for the proton $h_{11/2}$ intruder band in ^{113}Sb. In (a) the spin contribution of the rotating core has been subtracted, with the reference parameters shown. Also shown is the $\mathcal{J}^{(2)}$ moment for the yrast rotational band in ^{112}Sn, which shows a sharp (i.e., small-interaction) crossing at $\hbar\omega = 0.37$ MeV.

alignment gains can also be obtained from the dynamic moment of inertia by

$$\Delta i = \int (\mathcal{J}^{(2)} - \mathcal{J}_0^{(2)}) d\omega \qquad (1)$$

and the interaction strengths by

$$V_{\text{int}} = \frac{\Delta i^2/4}{\mathcal{J}_{\text{max}}^{(2)} - \mathcal{J}_0^{(2)}} , \qquad (2)$$

where $\mathcal{J}_0^{(2)}$ and $\mathcal{J}_{\text{max}}^{(2)}$ are the unperturbed and maximum value of the $\mathcal{J}^{(2)}$ moment of inertia, respectively. [Similar but incorrect expressions for V_{int} appear as Eq. (2) in Ref. [10] and Eq. (32) in Ref. [11]. The derivation leading to our Eq. (2) was suggested by Nazarewicz [12].]

Since the two band crossings in ^{113}Sb lie far enough apart in frequency to be separated in the $\mathcal{J}^{(2)}$ plot it is reasonable to use Eqs. (1) and (2) to obtain a direct measure of the interaction strength. With a value of $23\hbar^2$ MeV^{-1} for $\mathcal{J}_0^{(2)}$, the extracted values of the alignment gain are $(7.3 \pm 0.5)\hbar$ and $(4.3 \pm 0.4)\hbar$, in good agreement with the estimates obtained above, and the interaction strengths are 360 ± 60 keV and 210 ± 40 keV for the first and second crossing, respectively.

Comparing the properties of the observed crossings with those predicted with the cranking calculations, it is plausible to associate the second crossing with the rotational alignment of $g_{7/2}$ protons. If so, then the agreement between theory and experiment for the second crossing indicates that the mean-field approach describes the energies of and, more importantly, the interactions between the valence *proton* configurations with reasonable accuracy. Regarding the first crossing, however, there is a very large discrepancy between the ^{113}Sb experimental result and the cranked shell model prediction of $|V_{\text{int}}| \simeq 80$ keV. In addition, the value extracted for the same crossing in the ^{112}Sn ($Z = 50$) core nucleus is only $\simeq 20$ keV. The $\simeq 300$ keV difference between the interaction strength observed and that calculated with a mean-field approach is similar to the values estimated for band crossings in $i_{13/2}$ intruder bands in heavier nuclei [9], and suggests a residual interaction between valence high-j neutrons and protons which is not included in the calculation.

A large discrepancy is also apparent between the observed and calculated crossing frequencies for the rotational alignment of $h_{11/2}$ neutrons. In general, theory can reproduce the crossing frequencies in the nearby even-even Sn nuclei, to within 0.02 MeV. By comparison, the measured crossing frequency in the proton $h_{11/2}$ band in ^{113}Sb is $\hbar\omega = 0.46$ MeV, 0.09 MeV higher than in the core nucleus ^{112}Sn (see Fig. 3). Crossing-frequency shifts can be caused by a variety of effects, including shape changes induced by valence nucleons. We have calculated crossing frequencies for a range of deformations and estimate that at most a third of the observed frequency shift in the ^{113}Sb intruder band can be accounted for in this manner.

At a given deformation the frequency at which the ground-state and aligned two-quasiparticle (S-band) configurations cross is governed by the aligned spin of the two-quasiparticle configuration, and the energy gap between the two configurations at zero rotational frequency. The rotational alignment of $h_{11/2}$ neutrons contributes the same amount of aligned spin in the ^{112}Sn and ^{113}Sb crossings; thus the higher crossing frequency in ^{113}Sb is a direct consequence of an increase in the energy of the neutron $h^2_{11/2}$ S band, of approximately 400 keV. In the Nilsson-Strutinsky approach the energy gap at zero frequency is determined mainly by the effective pair gap and so, apart from the deformation effects discussed above, shifts in crossing frequency are commonly related to changes in the pairing interaction. Such an explanation is unlikely in ^{113}Sb, since the proton $h_{11/2}$ orbital does not lie close to the Fermi surface at zero rotational frequency and thus its occupation has only a small effect on the pairing energy. We propose that the shift in ^{113}Sb is most likely related to a strong high-j proton-neutron interaction, since it is the presence of the proton $h_{11/2}$ intruder which affects the neutron $h_{11/2}$ crossing, and since the second crossing shows no such effect.

In summary, a well-deformed rotational band built on the proton $h_{11/2}$ orbital has been observed to high spin and rotational frequency in the nucleus ^{113}Sb. Together with the measurement of the transition quadrupole moment this constitutes the first observation of the $h_{11/2}$ orbital as an "enhanced-deformation" intruder configuration, and confirms the shape coexistence thought to be present throughout this mass region. A band crossing due to the rotational alignment of $h_{11/2}$ neutrons is considerably delayed relative to bands in neighboring even-even nuclei, and is found to be perturbed by a residual interaction of approximately 300 keV. We conclude that although the quadrupole moment and excitation energy of the *proton* $h_{11/2}$ intruder band in ^{113}Sb are reasonably well predicted with a standard mean-field approach, a description of the *neutron* $h_{11/2}$ band-crossing properties requires a strong residual proton-neutron interaction.

This work is supported by the Natural Sciences and Engineering Research Council of Canada. The computer code for the calculation of potential-energy surfaces was kindly provided by J.-y. Zhang. The assistance of the staff of the TASCC facility is gratefully acknowledged, as are valuable comments from W. Nazarewicz and R. Wadsworth.

(a) Also at McMaster University, Hamilton, Ontario, Canada L8S 4M1.
(b) Visitor from Centre de Recherches Nucléaires, Strasbourg, France.
(c) Present address: AECL Research, Chalk River Laboratories, Chalk River, Ontario, Canada K0J 1J0.
(d) Present address: Manne Siegbahn Institute of Physics, S-10405 Stockholm, Sweden.

[1] A.K. Gaigalas, R.E. Shroy, G. Schatz, and D.B. Fossan, Phys. Rev. Lett. **35**, 555 (1975); Phys. Rev. C **19**, 1324 (1979).
[2] D.R. Lafosse, D.B. Fossan, J.R. Hughes, Y. Liang, P. Vaska, M.P. Waring, and J.-y. Zhang, Phys. Rev. Lett. **69**, 1332 (1992).
[3] K. Heyde, P. Van Isacker, M. Waroquier, J.L. Wood, and R.A. Meyer, Phys. Rep. **102**, 291 (1983).
[4] W. Nazarewicz, in *Contemporary Topics in Nuclear Structure Physics*, edited by R.F. Casten, A. Frank, M. Moshinsky, and S. Pittel (World Scientific, Singapore, 1988), p. 467.
[5] S.M. Mullins, I. Jenkins, Y-J. He, A.J. Kirwan, P.J. Nolan, J.R. Hughes, and R. Wadsworth, Phys. Rev. C **45**, 2683 (1992).
[6] R. Wyss, J. Nyberg, A. Johnson, R. Bengtsson, and W. Nazarewicz, Phys. Lett. B **215**, 211 (1988).
[7] W. Nazarewicz, R. Wyss, and A. Johnson, Nucl. Phys. **A503**, 285 (1989), and references therein.
[8] H. Harada, T. Murakami, K. Yoshida, J. Kasagi, T. Inamura, and T. Kubo, Phys. Lett. B **207**, 17 (1988); D.A. Viggars, H.W. Taylor, B. Singh, and J.C. Waddington, Phys. Rev. C **36**, 1006 (1987).
[9] R.A. Wyss and A. Johnson, in *Proceedings of the International Conference on High Spin Physics and Gamma-Soft Nuclei, Carnegie-Mellon University, Pittsburgh*, edited by J.X. Saladin, R.A. Sorensen, and C.M. Vincent (World Scientific, Teaneck, NJ, 1991), p. 123.
[10] S. Åberg, Nucl. Phys. **A520**, 35c (1990).
[11] R. Bengtsson, S. Frauendorf, and F.-R. May, At. Data Nucl. Data Tables **35**, 15 (1986).
[12] W. Nazarewicz (private communication).