CONF-870970--9

Fifth International Conf. on Nuclei Far From Stability. Sept 14-19, 1987 Ontario, Canada

OBLATE-PROLATE SHAPE COMPETITION IN Z = 34-38 NUCLEI

J. H. Hamilton, A. V. Ramayya, X. Zhao, C. F. Maguire, W.-C. Ma,
J. Kormicki, S. Wen, L. Chaturvedi, Z.-M. Chen
Vanderbilt University, Nashville, TN. 37235

T. M. Cormier, M. Satteson
University of Rochester, Rochester, NY. 14627

J. D. Cole
INEL, Idaho Falls, ID. 83415

R. B. Piercey, M. A. Herath-Banda
Space Astronomy Lab., Univ. of Florida, Gainesville, FL. 32601

E. F. Zganjar, M. O. Kortelahti
Louisiana State University, Baton Rouge, LA. 70803

G. A. Leander
UNISOR, Oak Ridge, TN. 37831

J. Eberth, N. Schmal, T. Heck, L. Cleemann, T. Mylaeus,
W. Neumann, M. Nolte, and M. Wiosna
University of Köln, Köln, W. Germany.

CONF-870970--20

DE88 002781

"The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. DE-AC05-84OR21400. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes."

ABSTRACT

Now magic numbers for deformed shapes are established at N and Z of 38 and N of 60. These shell gaps at large deformation (β - 0.4) are magic when the proton and neutron shell gaps reinforce each other. Other shell gaps for 34 and 36 are predicted to be important for oblate deformation. The competition between these oblate and the 38 prolate gaps as well as the 40 spherical shell gap are considered. In ^{71}Se coexistence of oblate (β - -0.24) and large prolate (β - 0.4) shapes are observed. In ^{72}Se the excited prolate band with large deformation which coexists with the near-spherical ground state is found to dominate the yrast spectrum to 28^+. The moment of inertia of this band is essentially that of a rigid body. This moment of inertia supports the suggestion that the "super deformation", β - 0.4, being observed in this region may be associated with a collapse of pairing.

INTRODUCTION

A new region of very large prolate ground state deformation (β - 0.4) associated with shell gaps at N and Z of 38 for such large prolate β was first reported in ^{74,76}Kr at the last conference on nuclei far from stability[1,2]. Based on those results and new data for ^{80}Sr (ref. 3), it was proposed[1,4] that this unusually large deformation for nuclear ground states arose from the reinforcing of the proton and neutron shape driving forces associated with the s

The submitted manuscript has been authored by a contractor of the U. S. Government under Contract No. DE-AC05-76OR00033. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so for U. S. Government purposes.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

gaps at $\beta \sim 0.4$ for N and Z of 38 as seen in the then available calculations of the Nilsson single particle levels. Simultaneously, new calculations of Möller and Nix[5] in a folded Yukawa plus single particle potential predicted this new region of very strong deformation centered around N = Z = 38. The single particle levels in this model likewise have gaps for 38 at $\beta \sim 0.4$, as shown in Fig. 1, which is the same for both protons and neutrons.[6]

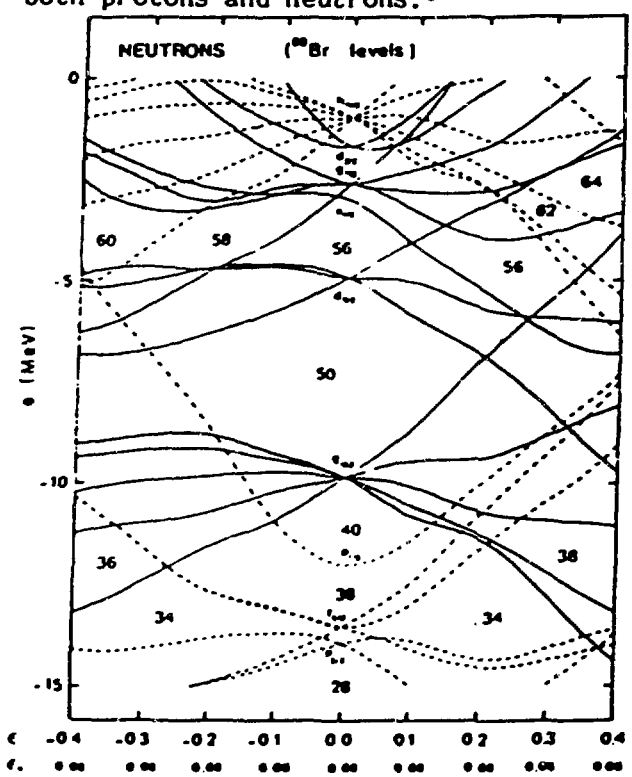


Fig. 1. The single-particle levels calculated with a folded Yukawa single-particle potential (ref. 6).

DEFORMED SHELL GAPS AND SHELL GAP REINFORCEMENT

Subsequently, we have shown that the shell gaps at $\beta \sim 0.4$ for N and Z of 38 (refs. 7, 8, 9) as well as N = 60 (refs. 7, 9) are new magic numbers but now for deformed shapes in addition to the well-known spherical magic numbers. These "deformed" magic numbers confirm the long-standing theoretical predictions of Brack et al.[10] that there should be "deformed" shell gaps which stabilize a deformed nuclear shape just as the spherical magic numbers (shell gaps at 2, 8, 20, ...) stabilize a spherical nuclear shape. The importance of the Z = 38 shell gap at large prolate deformation reinforcing the N = 38 and N = 60 shell gaps at the same large ($\beta \sim 0.4$) deformation to drive the nuclei in these regions to what may be called "super deformation" for nuclear ground states is illustrated in Fig. 2. This figure also illustrates the importance of spherical shell gap reinforcement as well. Both $^{88}_{38}Sr_{50}$ and $^{90}_{40}Zr_{50}$ have very large first excited 2^+_1 energies which are characteristic of spherical double magic (double

closed shell) nuclei like $^{208}_{82}Pb_{126}$. Here the 38, 40 weaker spherical subshell gaps are reinforced by the strong N = 50 spherical shell gap to produce spherical double magic nuclei. Even the weaker N = 56 spherical subshell gap can reinforce Z = 38 and 40 to keep the Sr and Zr nuclei strongly spherical out to N = 58. Then, at N = 60, there

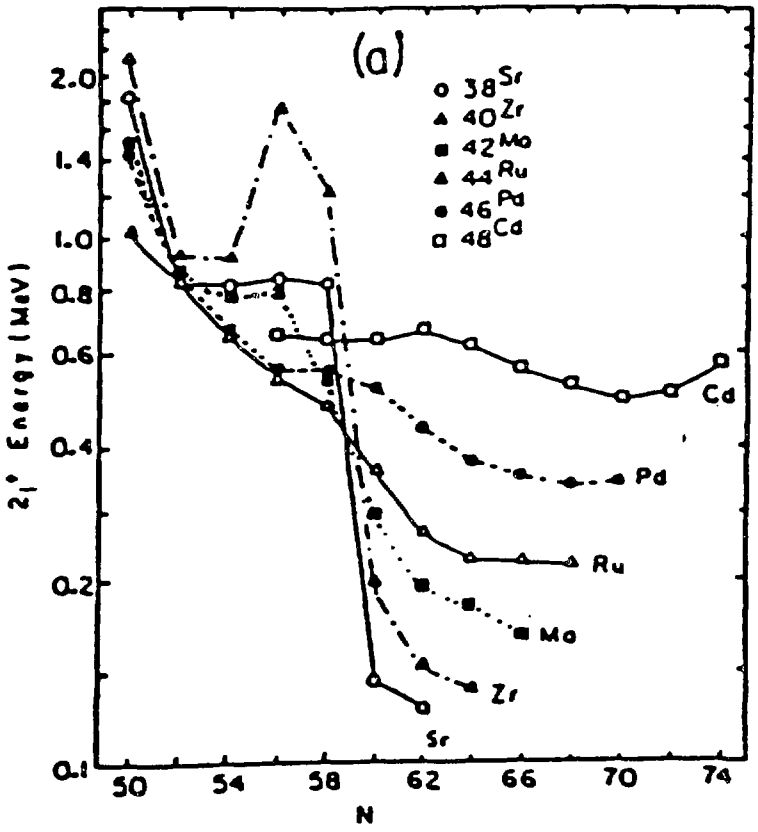


Fig. 2. The 2_1^+ energies of heavy Sr to Cd nuclei which show the sudden onset of large deformation for N = 60 in Sr and Zr nuclei with Z = 38 and 40.

is a sudden onset in $^{98}_{38}Sr_{60}$ and $^{100}_{40}Zr_{60}$ of unusually large ground state deformation. However, moving away from Z = 38 to Z $\geq$ 42 (Fig. 2) this sudden onset of deformation quickly disappears to show clearly the importance of the reinforcement of the Z = 38 and N = 60 shell gaps. Likewise, the reinforcement of the spherical shell gaps at Z = 40 and N = 56 quickly disappears as N or Z changes. Note it is the switch in reinforcement of two spherical to two different deformed shell gaps that leads to the suddenness of the onset of deformation in ^{98}Sr and ^{100}Zr. The switch in importance from the 40 spherical to the 38 deformed shell gaps is further seen in the recent discovery[11]

of $^{80}_{40}Zr_{40}$ which was found to be strongly deformed and not spherical double magic. The possibility of this switch was one of the arguments presented in the proposal to develop the UNISOR facility[12]. Reinforcing shell gaps indeed explain a wide range of changing deformation including, for examples, the sudden onset of deformation in the rare earths around Z = 64 and the disappearance of this suddenness as Z goes away from 64 (refs. 7, 9 for examples) and spherical double magic character of $^{156}_{64}Gd_{92}$.

Note these two new regions with ground state deformation (β ~ 0.4) may be called "super deformed" ground states by comparison with $\beta \lesssim 0.25$ for the well-known deformed rare earth and actinide ground states. This "super deformation" may be a signal that these nuclei are approaching the long-sought, pairing free structures but now at or near the ground state rather than at high spins as earlier predicted[13]. This possibility is discussed elsewhere in these proceedings[14].

OBLATE SHELL GAPS IN THE A = 70 REGION

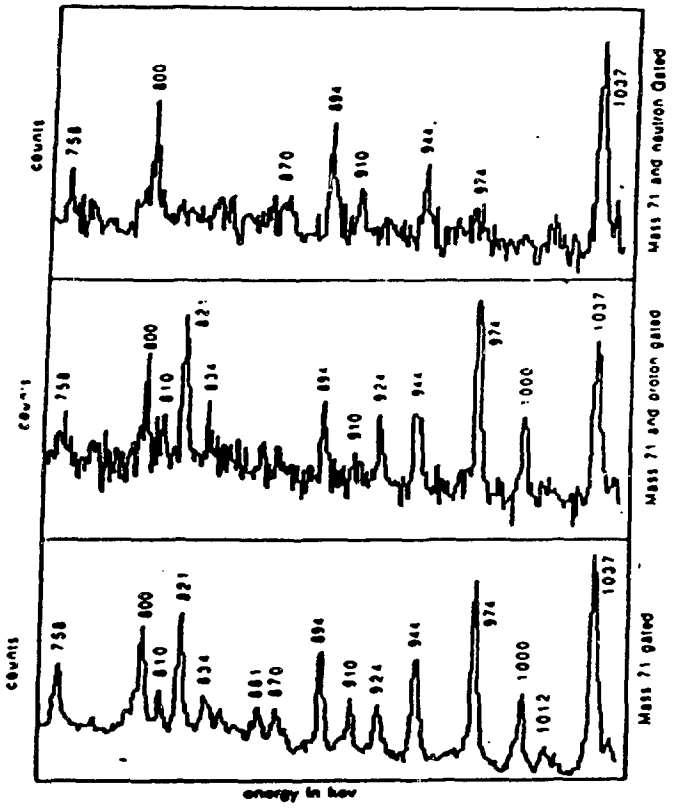
In Fig. 1 there are also shell gaps at other deformations such as N = Z = 34 for oblate deformation β ~ -0.25 and for N = Z = 36 large oblate deformation of β = -0.4. The large oblate shell gaps at N = Z = 36 could be theoretically expected to be as important as the N = Z = 38 shell gaps for the prolate shape with β ~ 0.4. However, based on the strong evidence that the prolate shell gaps can stabilize a deformed shape only when the proton and neutron shell gaps reinforce each other, one would expect that similar reinforcement would be necessary for the oblate shapes to be observed. Already the prolate shapes of $^{74,75,76}_{36}Kr_{38,39,40}$ show that the N = 38 prolate gap at β ~ 0.4 is stronger than the Z = 36 shell gap at β ~ -0.4. Nevertheless, it is important from the theoretical standpoint to establish if these oblate gaps at 34 and 36 can stabilize oblate shapes and in which nuclei.

Searches to identify a prolate to oblate phase transition in the ground states of nuclei in the A = 70 region was begun at the Recoil Mass Spectrometer (RMS) at the University of Rochester. One may also observe prolate-oblate transitions as functions of spin and energy in a given nucleus. One possible sequence to observe such a ground state phase transition is the Br nuclei going from $^{73}_{35}Br_{40}$ to $^{73}_{35}Br_{38}$ to $^{71}_{35}Br_{36}$. In our first RMS studies[15] we identified levels in $^{73,75}Br$ which have strong prolate ground state deformations with ^{73}Br with N = 38 having somewhat larger deformation than ^{75}Br (N = 40) as expected.

OBLATE-PROLATE COMPETITION IN $^{71}_{34}Se_{37}$

Further experiments were carried out at the University of Köln tandem and with the RMS at Rochester on the mass 71 region. Here we report our studies of $^{71}_{34}Se_{37}$. At Köln to help identify the levels in ^{71}Se, a multi-sector neutron detector was used to carry out n-γ, n-$\gamma(\theta)$, and n-γ-γ coincidence studies. A new five sector neutron detector (built by Vanderbilt and LSU) and four new NaI detectors (built at Vanderbilt) which were calibrated for fast protons were

Fig. 3. Gamma rays in coincidence with recoil mass 71 only, RM-71-protons and RM-71 neutrons from bottom to top, respectively.

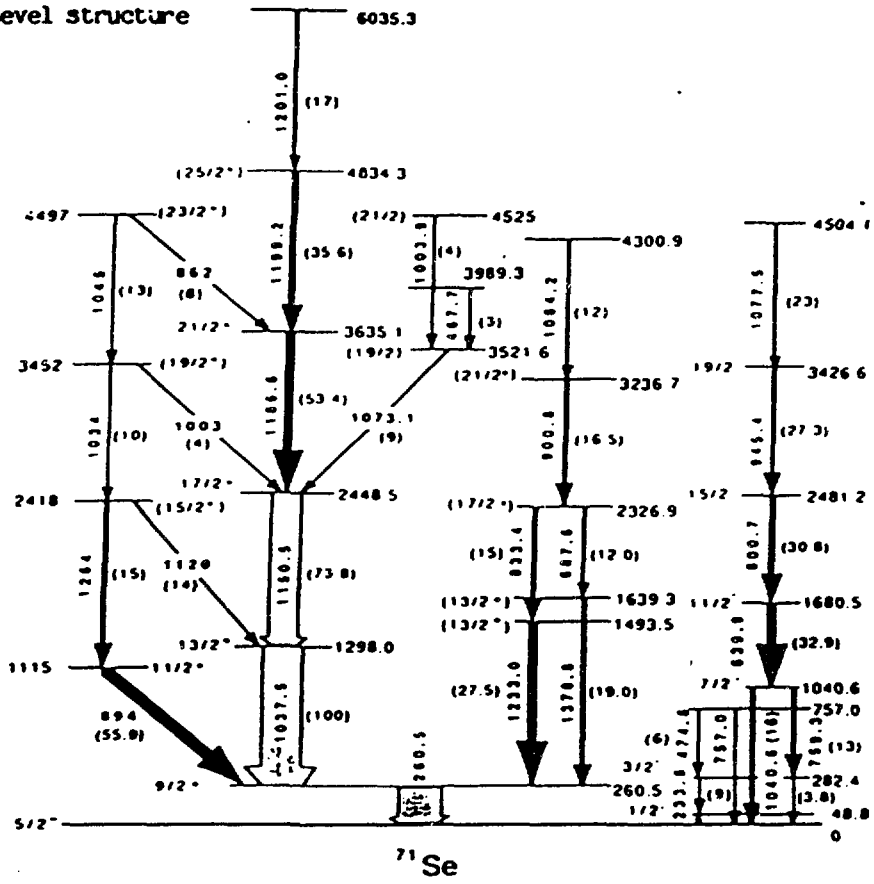


used to select coincidence gates along with a recoil mass gate from the Rochester RMS, to do recoil mass-γ, RM-n-γ, and RM-p-γ double and triple coincidences. The reaction $^{16}O + ^{58}Ni$ was studied with 41-64 MeV ^{16}O ions.

In Fig. 3 are shown partial γ-ray spectra with only a single recoil mass 71 gate, and with double RM-71-neutron and RM-71-proton gates. For example, the 894 keV transition is clearly enhanced in the RM-neutron gated spectrum compared to the RM-p gated one, and RM only gated one as are other transitions in ^{71}Se from levels populated in the (2p,n channel) to mass 71. Transitions in ^{71}As populated in the 3p channel to mass 71 are enhanced in the RM-proton gated spectrum. Combining the data from the Köln and Rochester experiments yielded the level scheme shown in Fig. 4. Of particular importance is the measured E2/M1 mixing ratio $\delta = 0.5 \pm 0.10$ for the 894 keV transition.

A theoretical analysis of the levels of ^{71}Se in which a deformed shell model of the nucleonic orbits, BCS pairing, the Strutinsky method to determine self-consistent shapes, and cranking or coupling

Fig. 4. Level structure of ^{71}Se.



of the quasiparticles to a triaxial rotor core in order to include non-adiabatic efects of rotation were used. A shell model potential of the Woods-Saxon type with the "universal" parameter set[16] was used with its shape specified by quadrupole (β), hexadecapole (β_4) and triaxial (γ) deformation coordinates[17]. The pairing interaction is given by Dudek et al.[18], the implementation of the Strutinsky and cranking procedures are described in ref. 17 and references therein, and the core-quasiparticle coupling is carried out as in ref. 19.

The potential energy of deformation for both positive and negative parity exhibits two coexisting equilibrium shapes with prolate and oblate axial deformations, respectively. This shape coexistence persists when the potential is cranked to modest rotational frequencies, however, the equilibrium deformations become slightly triaxial (in the collective sector).

The calculated axial deformations and relative energies of the band heads are given in Table I. The corresponding bands nicely account for the main features of the observed band structures in Fig. 4.

Table I. Calculated properties of the lowest prolate and oblate quasiparticle states of each parity. The Nilsson label is the conventional one (see ref. 20). The excitation energy E* is given relative to the lowest state for oblate and prolate shape separately.

	π	β	β_4	Nilsson Label	E* (keV)
oblate	-	0.24	-0.003	1/2[321]	(0)
oblate	+	0.24	-0.006	9/2[404]	8
prolate	-	0.38	0.004	3/2[312]	(0)
prolate	+	0.30	-0.006	3/2[431]	529

The lowest negative-parity levels and the positive parity $\Delta I = 1$ sequence to the left in Fig. 4, correspond to the oblate solutions, while the positive and negative parity high spin sequences to the right in Fig. 4 are identified with the prolate solutions. The moment of inertia for the high-spin sequences in Fig. 4 increases from left to right (taking into account rotational alignment), in qualitative agreement with the calculated deformations of Table I.

The $5/2^-$, $1/2^-$, $3/2^-$ level sequence of the ground state band is reproduced by a rotor-quasiparticle calculation for oblate or any oblatish triaxial shape at $|\beta| = 0.24$. This is essentially a decoupled $f_{5/2}$ structure, with wave functions that are roughly equal admixtures of the adiabatic 1/2[301], 3/2[321] and 1/2[321] orbitals. A test of this interpretation is provided by the γ-decay of the $3/2^-$ level. The calculated B(M1) rate is more than 3 times larger to the $1/2^-$ than the $5/2^-$ level, in agreement with the experimental branching ratio.

The large moment of inertia of the negative parity states above $7/2^-$ suggests that these states belong to the strongly deformed prolate band built on the 3/2[312] configuration. This configuration was predicted to be the ground state of ^{71}Se, some 450 keV below the lowest oblate state, but in light of the spectroscopic evidence discussed above and below it appears that an oblate shape is more favored in nature than in the model. It is surprising that only the signature corresponding to the spin states ...$7/2^-$, $11/2^-$,... is observed, since the other ($f_{5/2}$-like) signature is slightly favored in the model calculations. The $\Delta I = 1$ transitions that connect the two signatures are, however, expected to be an order of magnitude weaker than the observed $\Delta I = 2$ transitions.

For positive parity there are two disconnected sets of levels at high spin. The set to the right is connected by relatively low-energy E2 transitions and appears to belong to the favored signature of a decoupled $g_{9/2}$ band. Such a band would be based on the low-Ω $g_{9/2}$ suborbitals that lie near the Fermi level for prolate shape. The levels to the left in Fig. 4 form a $\Delta I = 1$ sequence on the $9/2^+$

level, and would thus appear to be associated with the oblate 9/2[404] orbital. There is a sizable signature splitting in this $\Delta I = 1$ sequence, which can be reproduced by assuming a triaxial (γ) deformation in the non-adiabatic model calculations. If the core moment of inertia and the γ deformation of the particle-rotor model are fitted to the observed spacings of the $9/2^+$, $11/2^+$ and $13/2^+$ levels, the resulting value of γ is 32°, closer to oblate than prolate but just barely. Such large deviations from axial symmetry are often needed to describe moderately deformed bands in odd-A nuclei[21,22]. The γ deformation of the rotor model may then be simulating the effect of dynamical shape fluctuations[23]. A predominantly oblate deformation is also implied by the measured mixing ratio of $\delta = +0.5 \pm 0.1$ for the $11/2^+$ to $9/2^+$ transition. In pure strong coupling[24],

$$\delta = \frac{\langle I-1 || M(E2) || I \rangle}{\langle I-1 || M(M1) || I \rangle} = \sqrt{\frac{5}{12}} \frac{Q_o \langle IK20 | I-1K \rangle}{(g_s s_z + g_\ell \ell_z - g_R j_z) \langle IK10 | I-1K \rangle}$$

For an odd neutron, g_s is negative and g_ℓ is zero, so Q_o must be negative to give a positive sign of δ. Inserting numbers for the present case: $I = 11/2$, $K = 9/2$, $g_s = -0.7 \times 3.83$, $g_R = 0.4$, $s_z = 1/2$ and $j_z = 9/2$ corresponding to a $g_{9/2,9/2}$ suborbital, and $Q_o = -1.5$b corresponding to $\beta = 0.24$, gives $\delta = +0.44$ in agreement with the measured value. Reasonable variations of the inserted numbers do not significantly affect the agreement between the oblate strong-coupling limit and the measured mixing ratio.

With triaxial deformation, however, the M1 reduced matrix element diminishes more than the E2 matrix element, and the mixing ratio becomes larger. At the γ deformation where the signature splitting is reproduced, the particle-rotor model gives a mixing ratio of +0.96, on the large side compared to experiment. Thus, the measured mixing ratio suggests that the shape is closer to axial oblate than is deduced from the signature splitting of the energies. Such a discrepancy between the triaxiality deduced from energies and M1 properties has recently been reported in rare earth nuclei also.[25]

Summarizing, the $^{71}_{34}Se_{37}$ levels clearly show the presence of the oblate deformation associated with the $Z = 34$ shell gap at $\beta \sim -0.25$ and the competition favors the strong prolate shell gap at $N = 38$ for $\beta \sim 0.4$. The $N = Z = 36$ shell gap at large oblate deformation is not seen in this work. Further studies to identify levels in $^{71}_{35}Br_{36}$ in search of this gap are in progress.

SHAPE COEXISTENCE AND "SUPER DEFORMATION" IN ^{70,72}Se

The coexistence of bands of levels built on near-spherical (probably small oblate) ground states and strongly deformed excited bands in $^{70,72}_{34}Se_{36,38}$ was established earlier[26,27]. The ground states of these nuceli are likely associated with the shell gaps for $Z = 34$ at oblate deformation $\beta \sim -0.25$ and the excited deformed band with the prolate $N = 38$ shell gap at $\beta \sim 0.4$. Recently the high spin levels of ^{70,72}Se have been extended to 14^+ and 28^+, respectively[28]. Plots

of the angular momenta as a function of gamma-ray energy for these nuclei are shown in Fig. 5. The deformed bands totally dominate the yrast spectra in these nuclei in sharp contrast to $^{68,70}_{32}Ge_{36,38}$ (with two less protons) where the ground state bands fork at low spins. What is most striking is the constant moment of inertia seen in ^{72}Se at high spins with the moment of inertia essentially the rigid body value. This constant rigid body moment of inertia gives additional support to the proposal[14] that these "super deformed" (β ~ 0.4) structures in this region may be arising from a strong reduction in pairing, even approaching a pairing free state.

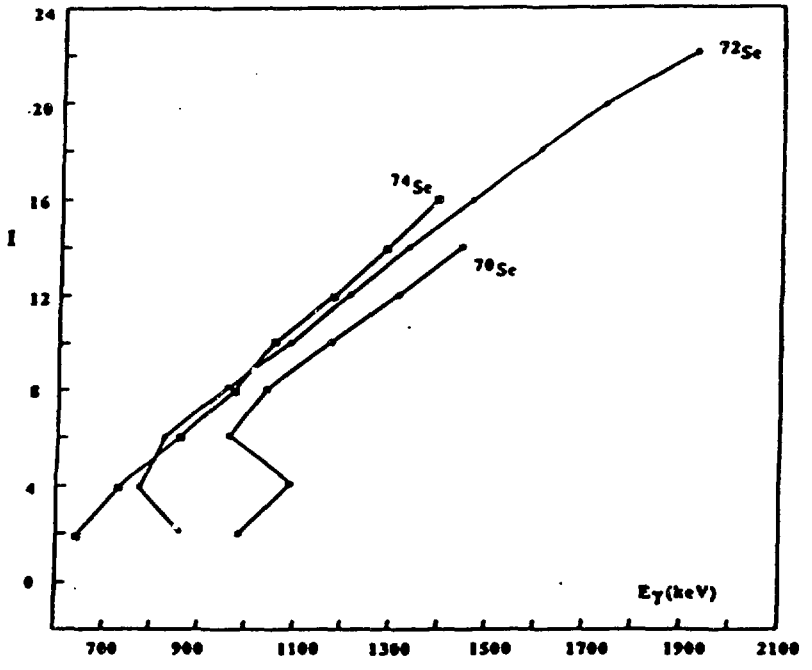


Fig. 5. Plot of the angular momentum as a function of the γ-ray energies for $^{70,72,74}Se$.

ACKNOWLEDGEMENTS

The work at Vanderbilt University, Louisiana State University and UNISOR is supported by the U.D. Department of Energy under Contract Nos. DE-AS05-76ER05034, DE-AS05-76ER04935, and DE-AC05-76OR00033, respectively. The University of Rochester Facility is supported by the National Science Foundation.

REFERENCES

1. J. H. Hamilton, R. B. Piercey, R. Soundranayagam, A. V. Ramayya, C. F. Maguire, X.-J. Sun, Z. Z. Zhao, J. Roth, L. Cleemann, J. Eberth, T. Heck, W. Neumann, M. Nolte, R. L. Robinson, H. J. Kim, S. Frauendorf, J. Döring, L. Funke, G. Winter, J. C. Wells, J. Lin, A. C. Rester and H. K. Carter, in Proc. IV Int. Conf. on Nuclei Far From Stability, CERN 81-09 (1981), pp. 391-396.

2. R. B. Piercey, Phys. Rev. Lett. 47, 1514 (1981).
3. M. Barclay, L. Cleemann, A. V. Ramayya, J. H. Hamilton, J. D. Cole, A. de Lima, W.-C. Ma, S. C. Pancholi, R. Soundranayagam, H. Yamada, W. Ellerby, R. L. Robinson, and W. Milner, private communication (1981) as reported in ref. 4.
4. J. H. Hamilton, Proc. Int. Symp. on Nuclear Collectivity, A. Arima and T. Marumori, eds., Tokyo: INS (1981), p. 87.
5. P. Möller and J. R. Nix, At. Data and Nucl. Data Tables 26, 165 (1981); Am. Chem. Soc. 183rd Nat. Conf., Abs. Nucl. 16 (1982).
6. R. Bengtsson, P. Möller, J. R. Nix, and J.-Y. Zhang, Physica Scripta 29, 402 (1984).
7. J. H. Hamilton, Proc. Int. Symp. on Nuclear Shell Models, M. Vallieres and B. H. Wildenthal, eds., Singapore: World Scientific (1985), p. 31.
8. J. H. Hamilton, A. V. Ramayya, C. F. Maguire, R. B. Piercey, R. Bengtsson, P. Möller, J. R. Nix, J.-Y. Zhang, R. L. Robinson, and S. Frauendorf, J. Phys. G: Nucl. Phys. 10, L87 (1984).
9. J. H. Hamilton, Progress in Particle and Nuclear Physics, Vol. 15, A. Faessler, ed., New York: Pergamon Press (1985), p. 107.
10. M. Brack, J. Damgaard, A. S. Jensen, H. C. Pauli, V. M. Strutinsky, and C. Y. Wong, Rev. of Mod. Phys. 44, 329 (1972).
11. C. J. Lister et al., elsewhere these Proceedings.
12. J. H. Hamilton, Izv. Akad. Nauk, USSR Ser., Fiz 36, 143 (1972).
13. B. R. Mottelson and J. G. Valatin, Phys. Rev. Lett. 5, 511 (1960).
14. L. K. Peker and J. H. Hamilton, elsewhere in these proceedings.
15. S. Wen, A. V. Ramayya, S. J. Robinson, C. F. Maguire, W.-C. Ma, X. Zhao, T. M. Cormier, P. M. Stwertka, J. D. Cole, E. F. Zganjar, R. B. Piercey, M. A. Herath-Banda, J. Eberth, and M. Wiosna, J. Phys. G: Nucl. Phys. 11, L173 (1985).
16. J. Dudek, Z. Szymanski, and T. Werner, Phys. Rev. C23, 920 (1981).
17. W. Nazarewicz, J. Dudek, R. Bengtsson, T. Bengtsson, and I. Ragnarsson, Nucl. Phys. A435, 397 (1985).
18. J. Dudek, A. Majhofer, and J. Skalski, J. Phys. G6, 447 (1980).
19. S. E. Larsson, G. Leander, and I. Ragnarsson, Nucl. Phys. A307, 189 (1978).
20. S. E. Larsson, et al., Nucl. Phys. A261, 77 (1976).
21. J. Meyer-ter-Vehn, Nucl. Phys. A249, 111 and 141 (1975).
22. H. Toki and A. Faessler, Phys. Lett. 63B, 121 (1976).
23. G. Leander, Nucl. Phys. A273, 286 (1976).
24. A. Bohr and B. R. Mottelson, Nuclear Structure, Vol. 2, New York: Benjamin (1975).
25. A. R. Mokhtar, et al., Proc. Int. Conf. on Nuclear Shapes, Vol. 1 (Crete, 1987), G. S. Anagnostatos, et al., eds., p. 62 and references therein.
26. J. H. Hamilton, et al., Phys. Rev. Lett. 32, 239 (1974).
27. A. Ahmed, et al., Phys. Rev. C24, 1486 (1981).
28. T. Mylaeus, J. Busch, J. Eberth, M. Liebchen, R. Sefzig, S. Skoda, W. Teichert, M. Wiosna, P. v. Brentano, K. Schiffer, K. O. Zell, A. V. Ramayya, K. H. Maier, H. Grawe, and A. Kluge, (to be publilshed).

DEC 0 1 1987

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.