THE STRONGLY DEFORMED NUCLEUS ^{100}Sr

S. Mattsson[a], R.E. Azuma[b], H.Å. Gustafsson[c], P.G. Hansen[d], B. Jonson[c], V. Lindfors[e],
G. Nyman[c], I. Ragnarsson[f], H.L. Ravn[c], and D. Schardt[c]
The ISOLDE Collaboration, CERN, Geneva, Switzerland.

Abstract

Experiments on the nucleus ^{100}Sr are reviewed. The activity was produced by fission with 600 MeV protons on a uranium target and after mass separation studied by gamma-ray and conversion-electron spectroscopy and by nanosecond lifetime measurements.

The theoretical implications of these results are discussed on the basis of a Nilsson-Strutinsky calculation.

1. Introduction

The region of deformation near (Z,N) = = (40,60) was found by Cheifetz et.al.[1] in measurements of radiations from prompt deexcitation of fission fragments, and recent experiments at the mass separators JOSEF[2] and OSTIS[3] have greatly extended our knowledge of this region. The domain of interest is illustrated in Fig. 1, which shows the systematics of the first 2^+ level in even-even nuclei of the elements around zirconium.

The proton number 40 has the character of representing a shell gap for spherical nuclei and at the same time also a shell gap for 2:1 prolate deformation[4]. This character is clearly confirmed by the systematics in Fig. 1, which shows spherical shape for the 50 closed neutron shell and the 56 closed $d_{5/2}$ subshell, while on the sides the neutron numbers 40 and 60, which like Z=40 favour prolate deformation, lead to new regions of deformed nuclei. The behaviour of the 2^+ energies for the nuclides with neutron number in the proximity of the mid-shell 1/2(50+82)=66 seems to be more smooth for molybdenum than for zirconium and strontium. Both strontium and zirconium exhibit a drastic drop in 2^+ energies between 58 and 60 neutrons, with the strontium being lowest in energy. In ^{100}Sr, the 2^+ state comes as low as 129.2 keV and the ratio E_{4^+}/E_{2^+} of 3.23, which is close to the

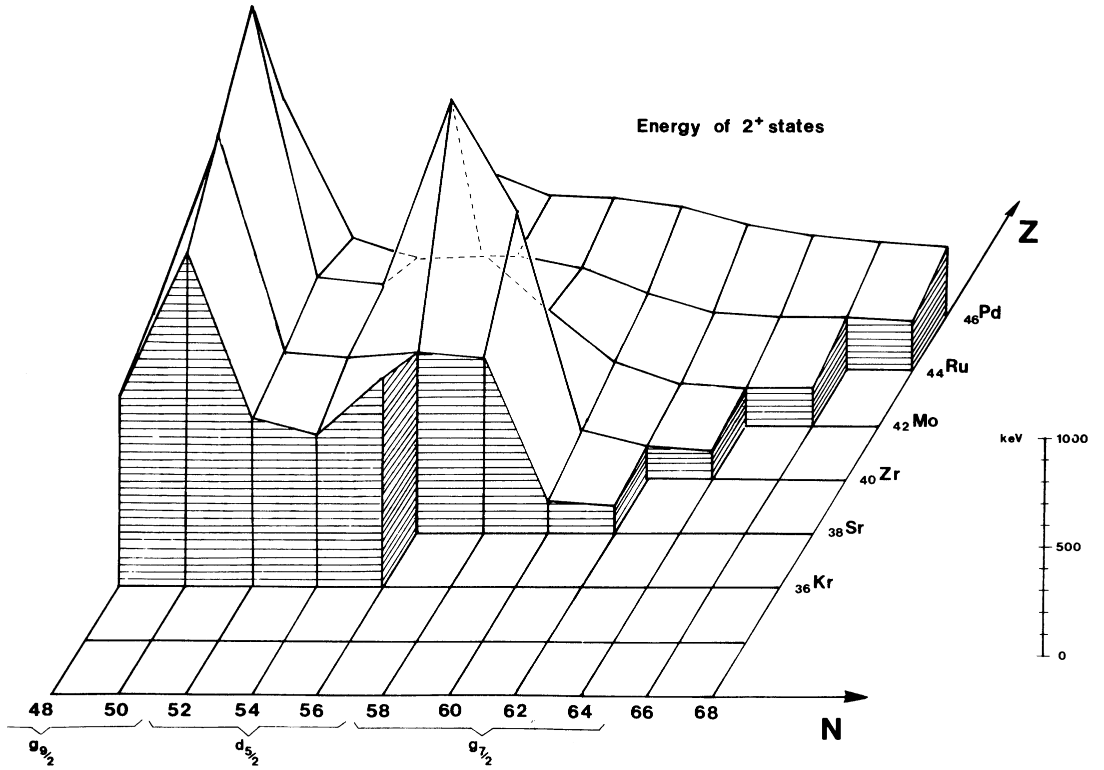

Fig. 1 Systematics of 2^+ energies in the mass A=100 region as a function of proton and neutron number projected from the neutron-rich side.
The data are taken from Ref. 1-6.

---

a, Dept. of Physics, Chalmers Univ. of Technology, S-412 96 Göteborg, Sweden
b, Dept. of Physics, Univ. of Toronto, Toronto Ontario M5S 1177, Canada
c, CERN-ISOLDE, CERN, CH-1211 Geneva, Switzerland
d, Inst. of Physics, Univ. of Aarhus, Dk-8000 Aarhus, Denmark
e, Dept. of Physics, Univ. of Helsinki, SF-00170 Helsinki, Finland
f, Dept. of Math. Physics, LTH, Sölvegatan 14, S-22007 Lund, Sverige

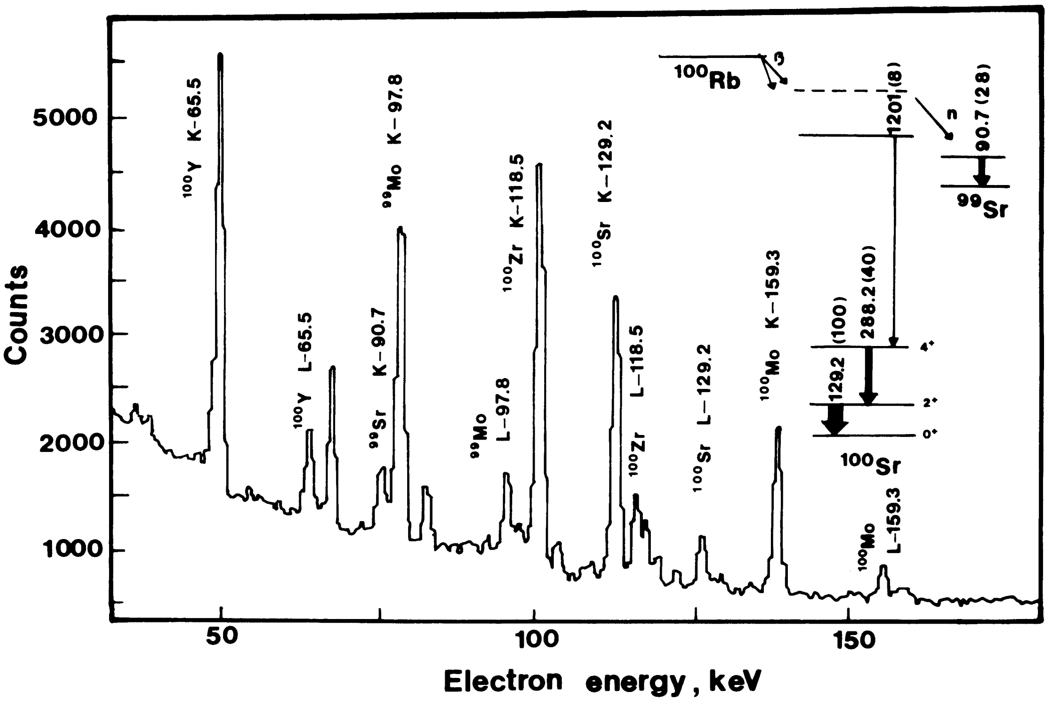

Fig. 2 Conversion electron spectrum obtained by a 3 mm x 3000 mm^2 Si(Li) detector and continuous on-line counting. The energy response of the detector was calibrated by observing well-known transitions in the daughter- and neighbouring elements. The inset shows a simplified level scheme of the strongest gamma transitions observed in the β-decay of 55 ms ^{100}Rb.

rigid rotor value of 10/3, is the highest yet found in this region.

2. Experimental procedures and results

The short-lived isotopes of rubidium were studied by γ-ray and conversion-electron spectroscopy and by nanosecond lifetime measurements. The radioactivity was produced by fission with 600 MeV protons impinging on a target of 46 g/cm^2 Uranium carbide at a temperature of about 2000°C, and was separated on-line at the ISOLDE Facility at CERN. The yield of ^{100}Rb was about 10^3 atoms per second.

The γ-ray spectrum observed in the β-decay of the 55 ms ^{100}Rb shows two γ-lines at 129.2±0.5 keV and 288.2±0.5 keV, interpreted as representing the lowest transitions in the ^{100}Sr ground-state rotational band$^{5)}$. From gamma-gamma coincidence and conversion electron measurements, the γ-lines were both found to be E2 transitions in coincidence. The E2 character of the 129.2 keV line could also be extracted from the K/L-ratio in the electron spectrum (Fig. 2). In the coincidence experiment, a new relatively strong transition of 1201±1 keV was found to populate the 4^+ level. The γ-line of 90.7±0.5 keV, which also decays with the 55 ms ^{100}Rb half-life$^{5)}$, was proved to belong to the delayed neutron daughter ^{99}Sr.

The lifetime of the 129.2 keV level has been determined by measuring delayed coincidences between β-particles and conversion electrons detected in 1 mm and 0.2 mm thick plastic scintillators.

The distribution of delayed coincidences shown in Fig. 3 reveals a single delayed component corresponding to a halflife of 5.15±0.20 ns. The period did not depend on the gate settings in the beta or electron energies.

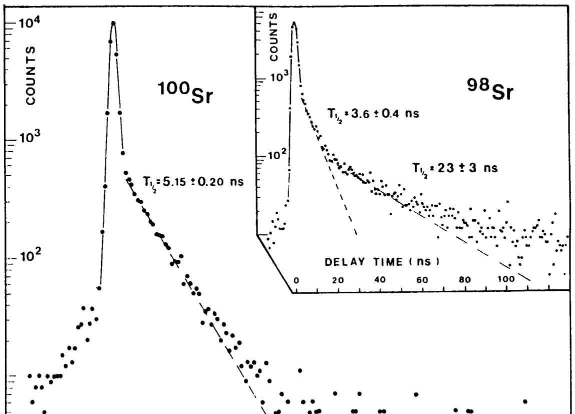

Fig. 3 Time spectrum observed at ^{100}Sr from β-ray conversion electron coincidences measured by two thin plastic scintillators. The experimental resolution was 1.8 ns FWHM. The corresponding spectrum obtained for ^{98}Sr is shown in the inset.

Similar measurements were performed on ^{98}Rb. The inset in Fig. 3 shows that in this case two delayed components are present. Our findings seem to be in excellent agreement with those of Schussler et.al.$^{3)}$, who explained the longer component as the halflife of the first excited 0^+-state in ^{98}Sr.

3. Excited 0^+ state

Part of the aim of the gamma and conversion electron experiments was to look for a possible low-lying excited $I^{\P}=0^+$ state in ^{100}Sr. As can be seen from Fig. 4, these

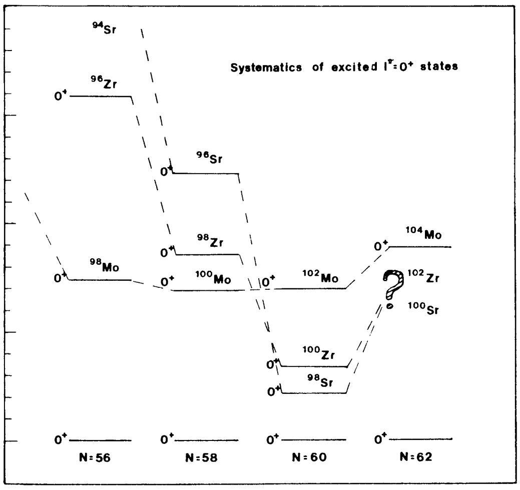

Fig. 4 Systematics of excited 0^+ states in the elements Sr, Zr, and Mo as a function of neutron number. The data are taken from Refs. 3, 6, 7.

0^+ levels are found at unexpectedly low energies in this mass region. In the present experiment, however, such a state, if it excists at low energy, was not possible to identify.

The systematics in Fig. 4 indicate that the low-lying 0^+ levels in Mo tend to change between 60 and 62 neutrons. Molybdenum is known to have more smooth systematics of the energy levels than zirconium and strontium. Therefore, in ^{100}Sr where the deformed shape is thought to be stabilized, the first excited $I=0^+$ level might be expected at higher energy than in ^{98}Sr. It should be pointed out that any low-lying state could have escaped detection if it was fed at the percent level. This because the experiment was performed with a newly developed high-efficiency surface ionizer, which gave us a certain amount of directly produced strontium and thus larger background.

To observe a detectable signal from an excited $I=0^+$ state in ^{100}Sr would require a low spin value of the β-decaying state in ^{100}Rb. In the decay of ^{98}Rb, two isomers with very small halflife difference were observed$^{3)}$. The fact that the first excited 0^+ state in ^{98}Sr is populated in a large amount, points to a β-decaying state of low spin value. Atomic hyperfine structure measurements$^{8)}$ give an uncertain spin I=0 as a result for ^{98}Sr. Similar measurements$^{8)}$ on ^{97}Rb point to $[431]3/2^+$ as the most likely proton-configuration (see contr. to this conf. by C. Ekström). For N=61 neutrons, the most likely neutron configuration for strong prolate deformation is $[411]3/2^+$. (See Fig. 5) The coupling of

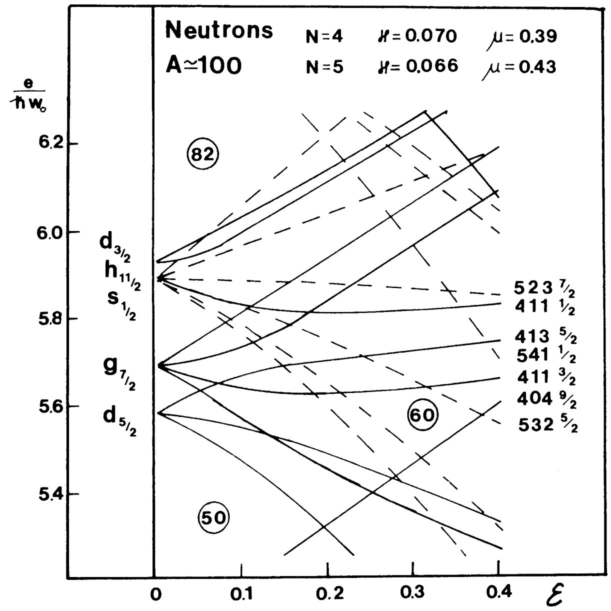

Fig. 5 Single particle levels in the A=100 region for the modified oscillator potential as a function of the deformation parameter ε. The parameters are those of neutrons given in the figure.

these single-particle configurations should, according to the empirical rule$^{9)}$, yield spin I=3 lowest in energy. An extrapolation of the two single-particle configurations coupling to ^{100}Rb, gives for protons $[431]3/2^+$ and for N=63 neutrons either the same as for N=61 or $[532]5/2^+$.

4. Discussion

The results of the experiments point to ^{100}Sr as a well-developed axial rotor. The B(E2) value for the $2^+ \to 0^+$ transition translates$^{10)}$ into an intrinsic quadrupole moment of 3.3b. By assuming prolate spherical shape and using the relation between ε and Q to second order $Q=4/5\ ZA^{2/3}\ r_0^{\ 2}\varepsilon(1+1/2\varepsilon)$, a deformation parameter ε of 0.29 is derived. Note that the first order tirm in ε alone would lead to an ε-value of 0.35.

We note that several theoretical calculations$^{11)}$ are able to explain the onset of permanent deformation around N=60. The "chameleon" character of the zirconium isotopes is explained by the proton number being a subshell gap for spheri al shapes, while Z=38 emerges as a substantial gap in the Nilsson diagram for deformation o ε=0.3 - 0.4 (see figure in contr. by C. Ekström). The calculations, however, have difficulties in accounting for the suddenness of the transition from spherical shape at N=56 to the strong deformation encountered at N=60.

The calculation shown in Fig. 6 with parameters as given in the caption gives rise to a family of potential-energy curves that agree well with experiment: ^{94}Sr with 56 neutrons comes out with a rather deep spherical minimum, ^{96}Sr is soft, and ^{98,100}Sr are deformed with a (prolate) minimum at ε=0.30, that for ^{100}Sr being deeper. The proton energy curve shown in the lower part of Fig. 6 for Z=38 explains why either very large or very small values of ε are favoured.

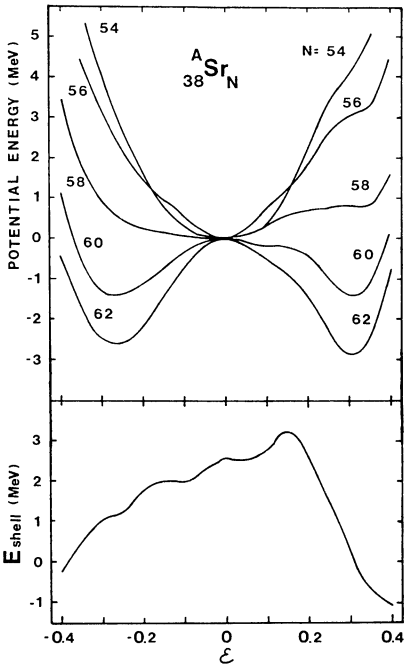

Fig. 6 The upper part of the figure shows potential-energy curves for Sr isotopes as a function of the deformation parameter ε. The lower part shows the corresponding proton shell energy for Z=38 as calculated by the Strutinsky prescription. A modified oscillator potential has been used with the following parameters: $\kappa_p=\kappa_N=0.08$, $\mu_p=0.30$, $\mu_N=0.22$. Only quadrupole deformation (ε) has been considered, but it has been verified that the hexadecapole degree of freedom (ε_4) is unimportant for these isotopes. The pairing strength parameter is taken as

$$GA(\tfrac{Z}{N}) = (19\pm7)\frac{N-Z}{A}\ \mathrm{MeV},$$

with $2\sqrt{10Z(N)}$ orbitals included in the calculation. Calculations based on the same set of parameters have also been carried out for the heavier elements. While the picture for zirconium is similar to that shown here, molybdenum and ruthenium have smaller deformations and a less abrupt transition to deformed shapes, in agreement with experimental results$^{1)}$.

The role of the minima calculated for oblate deformation (Fig. 6) is not clear: they are almost as deep as the minima at prolate deformations, and they are certainly expected to connect with these via the gamma degree of freedom. Thus, our calculations would have the heavy strontium isotopes to be soft vibrators in the gamma directions, while the high experimental E_{4^+}/E_{2^+} ratio excludes a strong triaxiality.

The moment of inertia of the ^{100}Sr ground state rotational band is 67 % of the prolate deformation rigid-body value, about the same as for ^{20}Ne and well above the values of 50-55 % (see Fig. 7) found in the rare earths and actinides. (If an oblate deformation were assumed, the moment of inertia would correspond to 82 % of the rigid-body value). The high value of the moment of inertia, possibly due to weaker pairing correlations than in the heavier nuclei, may be associated with the Z=38 "deformed gap" mentioned above. Further indications for reduced pairing effects come from the mass measurements by Epherre et.al.$^{13)}$, who find that the rubidium isotopes with N>50 have pairing energies much smaller than expected.

Attempts to explain the abrupt onset of deformation and occurrence of very low-lying excited 0$^+$ states have been made re-

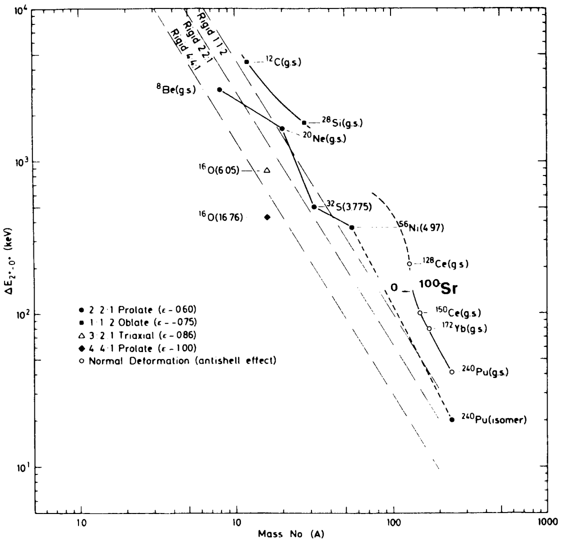

Fig. 7 Plot of rotational-type 2$^+$ energies for even-even nuclei over the entire mass region in logarithmic scales. A rotation on the basis of a rigid moment of inertia of any of the considered spheroidal shapes, with axis ratios of 4:1 prolate, 2:1 prolate and 1:2 oblate, corresponds to the three straight (dashed) lines drawn in the figure. The figure is taken from Ragnarsson et.al.$^{12)}$

cently by Federman and Pittel[14] with calculations on proton-neutron interaction. In a purely independent particle picture, the Zr isotopes with Z=40 have the $1g_{9/2}$ proton orbital completely empty and the $1g_{7/2}$ neutron orbital begins to fill after N=62. This picture is modified by residual n-n and p-p interactions, which distribute nucleons over all active orbitals by configuration mixing. Neutrons and protons simultaneously filling selected partner orbitals can lead to strong n-p correlations and consequently to deformations. Mutual polarization of nucleons into the $1g_{9/2}$ proton and $1g_{7/2}$ neutron orbitals can occur if the gain in n-p interaction energy exceeds the loss in single-particle plus pairing energy.

The idea that n-p force favours large $1g_{9/2}$ proton and $1g_{7/2}$ neutron occupation probabilities and that this is closely related to the onset of deformation is consistent with the Nilsson model. By examining the relevant deformed proton orbitals, one finds that for sufficiently large prolate deformation, the two lowest Nilsson configurations beyond Z=38 correspond to $1g_{9/2}$, and not to $2p_{1/2}$ proton orbital.

In conclusion, a new region of strongly deformed nuclei is emerging. More experiments are needed, especially atomic hyperfine structure measurements that unambiguously can tie down the Nilsson assignments of the odd nucleons.

Acknowledgements

The authers are grateful to Dr C.Ekström for valuable comments on this paper.

References

1. E. Cheifetz, R.C. Jared, S.G. Thompson, J.B. Wilhelmy.
   Phys. Rev. Lett. 25 (1970) 38
   E. Cheifetz, H.A. Selič, A. Wolf, R. Chechik, J.B. Wilhelmy.
   Inst. Phys. Conf. Ser. No. 51 p. 193
   Nuclear Spectroscopy of Fission Products, Lane-Langevin, Grenoble, 21-23 May, 1979.
2. K. Sistemich, G. Sadler, T.A. Khan, H. Lawin, W.-D. Lauppe, H.A. Selič, F. Schussler, J. Blachot, E. Monnand, J.P. Bocquet, B. Pfeiffer
   Z. Phys. A289 (1977) 225
   T.A. Khan, W.-D. Lauppe, K. Sistemich, H. Lawin, G. Sadler, H.A. Selič
   Z.Phys. A282 (1977) 283
   T.A. Khan, W.-D. Lauppe, K. Sistemich, H. Lawin, H.A. Selič
   Z. Phys. A284 (1978) 313
   K. Sistemich, W.-D. Lauppe, H. Lawin, H. Seyforth, B.D. Kern
   Z. Phys. A289 (1979) 225
3. F. Schussler, J.A. Pinston, F. Monnand, A. Moussa, G. Jung, E. Koglin, B. Pfeiffer, R.V.F. Janssens, J. van Klinken
   Nucl. Phys. A339 (1980) 415
4. R.K. Sheline, I. Ragnarsson, S.G. Nilsson
   Phys. Lett. B41 (1972) 115
5. R.E. Azuma, G.L. Borchert, L.C. Carraz, P.G. Hansen, B. Jonson, S. Mattsson O.B. Nielsen, G. Nyman, I. Ragnarsson, H.L. Ravn,
   Phys. Lett. 86B (1979) 5
6. Table of Isotopes, 7th ED. Eds. C.M. Lederer and V.S. Shirley, (John Wiley & Sons, New York, 1978)
7. K. Sistemich, W.-D. Lauppe, H. Lawin, H. Seyfarth, B.D. Kern,
   Z. Physik, A289 (1979) 225
8. C. Thibault, F. Touchard, S.Byttgenbach, R. Klapisch, M. de Saint-Simon, H.T. Duong, P. Jacquinot, P. Juncar, S. Liberman, P. Pillet, J. Pinard, J.L. Vialle, A. Persnelle, G. Huber, Hyperfine structure and isotope shifts of the D_2 line of $^{76-98}$Rb and some of their isomers. Submitted to Phys. Rev. C.
9. C.J. Gallagher Jr., S.A. Moszkowski,
   Phys. Rev. 111 (1958) 1282
10. P.H. Stelson and L. Grodzins,
    Nucl. Data A1 (1965) 21
11. I. Ragnarsson, Proc. Conf. on Properties of nuclei far from the region of beta stability.
    (Leysin, 1970) CERN 70-30 (1970) p. 847
    A. Faessler, J.E. Galonska, U. Götz, H.C. Pauli,
    Nucl. Phys. A230 (1974) 302
12. I. Ragnarsson, S.G. Nilsson, R.K. Sheline
    Physics Reports 45 (1978) 1
13. M. Epherre, G. Audi, C. Thibault, R. Klapisch, G. Huber, F. Touchard, H. Wollnik
    Phys. Rev. C19 (1979) 1504
14. P. Federman, S. Pittel
    Phys. Lett. 69B (1977) 385
    Phys. Rev. C20 (1979) 820.

DISCUSSION

E.R. Flynn: I disagree with the interpretation that the first excited 0^+ of ^{96}Zr is related to the rotational states but is more related to a pairing vibration at the N=56 subshell closure. A similar situation may exist in Sr.

I. Ragnarsson: In another contribution to this conference (Bengtsson, Ragnarsson, Zhang and Åberg), it is demonstrated that the 0^+ states of the spherical nuclei ...,^{96}Zr, ^{98}Zr, can be considered to form one band while the 0^+ states for the deformed ^{102}Zr, ^{104}Zr, ... form another band (fig. 3 of the mentioned contribution). These bands then cross close to N=60. This suggests two coexistent close-lying 0^+ states for ^{100}Zr. Away from N=60 the two bands diverge rapidly. Thus, one could expect coexistent 0^+ states with a spacing of 1-1.5 MeV for N=58 and N=62 while further away from N=60, the energy differences become larger and it becomes difficult to observe any coexistence. I would thus agree that the first excited 0^+ state of ^{96}Zr is probably not (or very little) connected with deformed shape. A similar situation as for the Zr isotopes is expected for the Sr-isotopes.

J.B. Wilhelmy: Are the excited 0^+ levels in ^{98}Sr and ^{100}Zr close to the calculated oblate minimum in the potential energy surface? Is there any experimental evidence for a rotational band built on these levels?

I. Ragnarsson: It is true that most potential-energy surface calculations in the neutron-rich Sr/Zr region give one oblate and one prolate minimum of about equal depth. However, in the γ-plane there is no or a very small barrier between the two minima. Furthermore, similar calculational results are obtained also in other regions of the nuclear chart while (to my knowledge) no firm experimental evidence for large oblate deformation (at low spin) has been presented for nuclei above the sd shell region. Thus it does not seem probable that the calculated oblate minima in ^{98}Sr and ^{100}Zr would show up as excited 0^+ states.

F. Tondeur: I would like to make a comment about the theoretical prediction of a strongly oblate minimum in the region of ^{100}Zr, ^{102}Zr, ^{100}Sr ... etc. The results I have obtained (Nucl.Phys. A359 (1981) 278 and this conference) suggest the existence of a very soft potential energy surface from $\varepsilon = 0.3$ to $\varepsilon = 0.1$, which is very different from your prediction, and which could be of some importance for the interpretation of the first 0^+ excited state.