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SATURATION OF DEFORMATION AT $N = 60$ IN THE Sr ISOTOPES

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From the lifetime of $t_{1/2} = 3.91\,(16)$ ns for the 2^+ state in ^{100}Sr a deformation parameter of $\beta = 0.40\,(1)$ has been derived. Within the given uncertainties, this value is equal to the recently determined β-parameters for ^{98}Sr and ^{99}Sr, indicating that in the Sr isotopes saturation of deformation is reached immediately at its onset well before neutron midshell. This behaviour is reflected by the »twin« character of ^{98}Sr and ^{100}Sr with identical features of their unperturbed ground-state rotational bands. These observations are discussed in terms of strong two-nucleon interactions.

In the $A = 100$ region of neutron-rich nuclei, besides $_{39}$Y and $_{40}$Zr the isotopes of $_{38}$Sr exhibit the fastest known shape transition at $N = 60$. While $^{96}\mathrm{Sr}_{58}$ has the character of an anharmonic vibrator with the 2_1^+ level at 815 keV[1)], its odd-neutron neighbour $^{97}\mathrm{Sr}_{59}$ shows shape coexistence with a spherical ground-state and a deformed band head at 585 keV[2)], whereas the next heavier even-even isotopes $^{98}\mathrm{Sr}_{60}$ and $^{100}\mathrm{Sr}_{62}$ exhibit ground-state rotational bands[3,4)]. From the systematics of the 2_1^+ energies of 145 keV and 129 keV, respectively, together with their lifetimes resulting in quadrupole deformation parameters β of 0.32[3,4)] and 0.35[4)], the generally observed increase of deformation towards neutron midshell seemed to be verified also for the Sr isotopes. However, the more recent lifetime measurements of the first excited states in $^{98}\mathrm{Sr}_{60}$[5)] and $^{99}\mathrm{Sr}_{61}$[6)] yielded β-parameters of 0.39 and 0.38, respectively, indicating the opposite trend of slightly decreasing deformation beyond $N = 60$. Therefore, in order to clarify the rather peculiar situation for the Sr isotopes, we have remeasured the lifetime of the 2_1^+ state in $^{100}Sr_{62}$ with techniques improved over those used in the previous experiments[3,4].

The isotope ^{100}Sr was produced at CERN-ISOLDE as the β-decay daughter of 53 ms ^{100}Rb by bombarding a 12 g/cm^2 uranium carbide target with 600 MeV protons. After fast diffusion from the target to a surface-ionisation source, the extracted Rb isotopes were mass separated. The target/ion source system was kept at a rather low temperature in order to minimize the ionisation of Sr. Apart from ^{100}Rb and its β-decay isobars, also activities of the $A = 99$ chain were observed which originated from β-delayed neutron decay of ^{100}Rb. For the lifetime measurement the γ-rays were detected with a small high-purity Ge detector (area 4.9 cm^2, thickness 1.3 cm) and a BaF_2 scintillator (area 7 cm^2, thickness 1.5 cm). The energy resolution at 122 keV was 0.6 and 36 keV, respectively. Among different experimental set-ups, the above detector combination was the optimum choice with regard to energy and timing resolution, detection efficiency, and limited beam time available. In addition, in view of the expected lifetime of several nanoseconds, $\gamma\gamma$ t-coincidences were recorded simultaneously using above the mentioned small and a large volume Ge detector (efficiency 27%, energy resolution 1.7 keV at 1.33 MeV). This yielded an independent lifetime determination as well as an extension of the decay scheme of ^{100}Rb[7]. The signals, both energies and time, were recorded in listmode. The time spectra were sorted off-line, corrected for contributions from the Compton background in the γ-gate and subsequently analysed by the centroid-shift method. In addition, the good timing resolution of the Ge-BaF_2 detector system (FWHM = 4.2 ns) allowed the application of an unfolding method[8]. This procedure is superior to the commonly used technique of just fitting the slope of the time spectrum, since it takes into account the detailed response function. For its determination, calibration data were taken from off-line measurements of a ^{152}Eu source, and from on-line measurements of known lifetimes in the $A = 98$ and 100 chains deduced from the centroid-shift method in the course of the ^{100}Sr experiment[6].

During 40 h of beam time, about 10^7 coincidence events belonging to ^{100}Rb decay or its daughter activities have been accumulated with the Ge-Ge argument, and $3.3 \cdot 10^6$ events with the Ge-BaF_2 detector system. The time spectrum of the 288 keV (Ge) — 129 keV (BaF_2) coincidences is shown in Fig. 1. In this case, a particularly careful setting of the energy gates was necessary, since in the energy projection of the BaF_2 scintillator the 129 keV γ-line partially overlaps with a 91 keV γ-transition from the 288 keV — 91 keV cascade in ^{99}Sr[6]. In order to reject contributions from this latter cascade, a narrower gate on the 129 keV γ-line had to be set, however at the expense of somewhat lower statistical accuracy. Table 1 summarizes the lifetime values obtained for different energy gates and both detector arrangements. For the Ge-BaF_2 system, the agreement between the results from the centroid-shift (column I) and the unfolding method (column II) is good. It is interesting to note that the lifetime deduced from a broader BaF_2 gate (500—1000 keV; see line 2) is slightly longer than the adopted values from lines 1 and 3. This result suggests possible interference from lifetimes of higher excited states[7] through Compton coincidences and demonstrates the importance of energy selectivity in such measurements.

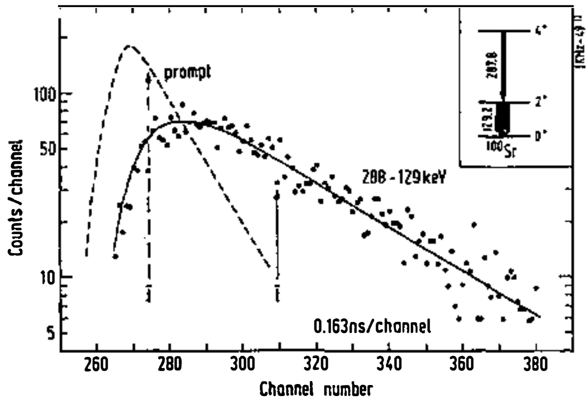

Fig. 1. Time distribution of the 288 keV (Ge detector) — 129 keV (BaF_2 scintillator) coincidences. The dashed line represents the response function of the prompt spectrum; the tail at its right-hand side is due to electronic effects. The solid line represents a fit to the total time distribution displayed in the figure. Centroids ($\bar{t}$) of the prompt and delayed time spectra are indicated by vertical arrows.

TABLE 1.

E_γ [keV]		Lifetimes $t_{1/2}$ [ns]		
Ge	BaF_2	I	II	adopted
129	288	3.91(24)	3.86(19)	3.88(19)
129	>500	4.17(18)	4.18(16)	4.18(16)
288	129	3.93(30)	4.06(30)	4.00(30)
129	288	3.7(5)		

Results of the analysis of the ^{100}Sr time spectra gated by the $2^+ \rightarrow 0^+$ (129 keV) and the $4^+ \rightarrow 2^+$ (288 keV) transitions in the small Ge detector with different energy gates in the BaF_2 scintillator (lines 1—3), and in the large Ge detector (line 4). Lifetimes $t_{1/2}$ (ns) deduced from the centroid-shift method (column I), from the unfolding method (column II) and adopted values are presented. The given uncertainties include standard deviation and systematical errors.

The weighted average of the lifetime of the 2_1^+ state in ^{100}Sr from the 129 keV — 288 keV and 288 keV — 129 keV coincidences (lines 1 and 3 in Table 1) is $t_{1/2} = 3.91(16)$ ns. This value is definitely shorter than the lifetime of 5.15(20) ns reported earlier[4]. The discrepancy may be due to the technique used in Ref. 4 where delayed time distributions between 8-particles and γ-transitions, the latter detected by their conversion electrons in a plastic scintillator, were recorded. This method offers a good timing resolution, but suffers from the lack of energy selectivity. In the former experiment, presumably a contribution from the — at that time unknown — excited 0^+ state at 331 keV in ^{100}Zr has disturbed the ^{100}Sr measurement. This 0^+ level has a lifetime of 5.4 ns[6] and decays to the ground-state of ^{100}Zr by an E0 transition.

Our new result for the lifetime of the 2_1^+ level in ^{100}Sr leads to values of $B(E2, 2^+ \rightarrow 0^+) = 103\,(5)$ W. u. and of $\beta = 0.40\,(1)$. When compared to $^{98}Sr_{60}$ (see Table 2) and $^{99}Sr_{61}$[6], these values imply that there is *no* decrease in defor-

TABLE 2.

G.-s. band properties	$^{98}Sr_{60}$		$^{100}Sr_{62}$
$B(E2, 2^+ \rightarrow 0^+)$ W. u.	94(3)	[106(3)]	103(5)
Q_0 barn	3.56(6)	[3.78(6)]	3.79(8)
β	0.39(1)	[0.40(1)]	0.40(1)
$E_\gamma(2^+ \rightarrow 0^+)$ keV	144.6	[121.3]	129.2
J/J_{rig}	0.74		0.72

Comparison of ground-state band properties in ^{98}Sr and ^{100}Sr. Values in brackets result from mixing calculations[9] for an unperturbed ground-state band in ^{98}Sr (see text). For connecting Q_0 and β we use $Q_0 = (9/5\pi)^{1/2} ZR^2\beta(1 + 0.158\beta)$. The moment of inertia is extracted from $E_\gamma(4^+ \rightarrow 2^+)$ with $a_{rig} = 36/(1 + 0.315\beta) A^{5/3}$ (MeV) (1 barn = 10^{-28} m^2).

mation for $^{100}Sr_{62}$, but rather a *saturation*. This result is surprising in that saturation does not occur at neutron midshell as usually observed, but already at the sudden onset of deformation at $N = 60$. Our observation is in qualitative agreement with results from recent laser spectroscopic studies[10]. Although deformations derived from r. m. s. values of nuclear radii are basically different (since besides static they also contain dynamic components) from those deduced from $B(E2)$ values, the general trend appears to be the same. The saturation of deformation at $N = 60$ is most evident when considering the »twin« character of the two even-even isotopes ^{98}Sr and ^{100}Sr (see Fig. 2 and Table 2). It is true that the

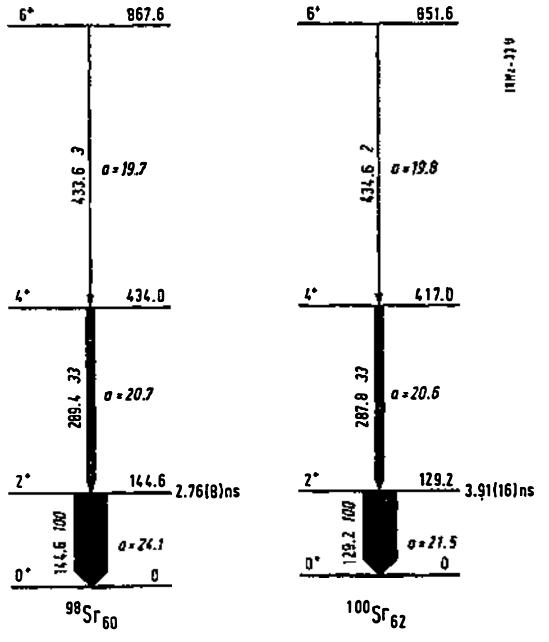

Fig. 2. Ground-state bands of ^{98}Sr and ^{100}Sr. For a better representation of the »twin« character of the two isotopes the level energies are adjusted to the 2^+ state. The values of the inertial parameter a [keV] indicate for both rotational bands an increasing rigidity with increasing angular momentum.

energy of the $2^+ \rightarrow 0^+$ transition in ^{100}Sr is 16 keV lower than that in ^{98}Sr, so that at first glance one might conclude that ^{100}Sr is a more rigid rotor, but the experimental 2^+ energy of 145 keV in ^{98}Sr seems to result from the mixing between the strongly deformed ground-state and the weakly deformed or spherical excited 0^+ level at 216 keV which repel each other. The mixing calculations of Mach et al.[9], for example, yield an unperturbed 2_1^+ level energy in ^{98}Sr of 121keV, in very close agreement with the 129 keV for ^{100}Sr. On the other hand, the ground-state band of ^{100}Sr seems to be very little perturbed. Hence, a coexisting 0^+ state, if present at all, should lie much higher in energy. The lowest candidate for an excited 0^+ state in our preliminary level scheme of ^{100}Sr lies at 1521 keV[7].

With practically identical features for the unperturbed ground-state band properties (collectivity of the $2^+ \rightarrow 0^+$ transition $B(E2)$, quadrupole moment Q_0, deformation parameter β, inertial parameters a, and E_γ of the $4^+ \rightarrow 2^+$ and (the new) $6^+ \rightarrow 4^+$ transitions) ^{98}Sr and ^{100}Sr behave like »twin« rotors. So far, such close similarity between neighbouring isotopes has only been observed for $_{68}$Er and $_{70}$Yb[11] and for the very recently studied neutron-rich $_{44}$Ru isotopes[12], but in all these cases the »twin« character develops at neutron midshell after a smooth shape transition extending over several isotopes. Hence, ^{98}Sr and ^{100}Sr are unique in that they represent the only example of »twins« just *at* the onset of strong deformation, well before neutron midshell.

It is interesting to point out in this context, that the situation for the isotopes of $_{40}$Zr with corresponding neutron numbers is slightly different. Although the deformation parameter β for an unperturbed ground-state band in $^{100}Zr_{60}$[6,9] seems to be equal (within the given uncertainties) to that in ^{102}Zr[13,14], the energies of the $4^+ \rightarrow 2^+$ and $6^+ \rightarrow 4^+$ transitions[12] differ by 27 keV and 11 keV, respectively, indicating a small increase of deformation when going from $N = 60$ to 62.

The situation for nuclei around $Z = 40$ and $N = 60$, and the saturation of quadrupole deformation in the Sr isotopes in particular, may be interpreted in terms of strong two-particle correlations[15–18].

In a phenomenological approach, the quartet model of Daley et al.[15] predicts the ability of a nucleus to deform according to the number of »quartetted« bosons assuming that *all* two-nucleon correlations (pp, nn and pn) are strong. This prescription reproduces quite well the 2_1^+ pattern in the rare-earth[15] and in the $A = 100$ regions[17]. For the latter region, when counting the nn- and pp-valence pairs from the doubly closed shell nucleus $^{78}Ni_{50}$ up to midshell ($Z = 39$, $N = 64$), deformation should reach its maximum in $^{98}Sr_{60}$ with the largest possible number of 5 (ppnn) quartets and no unquartetted bosons left. Within this model, also saturation of deformation at $N = 60$ is predicted since in $^{100}Sr_{62}$ one (nn)-pair remains unquartetted which does not contribute to further increase the collectivity in the Sr isotopic chain.

In a more microscopic way, the saturation of deformation in the $N \geq 60$ Sr isotopes can also be interpreated exclusively in terms of the residual proton-neutron interaction. The Sr, Zr region has been discussed in Ref. 16 where the p-n residual interaction at the same time diminishes the proton sub-shell gap between the $2p_{1/2}$ and $1g_{9/2}$ orbitals and creates the condition of two open valence shells such that strongly deformed shapes can develop. In a Nilsson model, *monopole* effects on the proton single-particle energies coming from the residual p-n interaction can be incorporated implicitly by slight variations of the μ-parameter as a function of neutron number. Moreover, due to the residual p-n *quadrupole* interaction, the binding energy associated with the occupation of certain Nilsson levels can become quite large. This is especially so when protons and neutrons occupy both up- or down-sloping Nilsson orbitals[18]. For $^{98,100}Sr$ this situation is presented in Fig. 3 where besides the proton (for $Z = 38$) and neutron (for $N = 60$

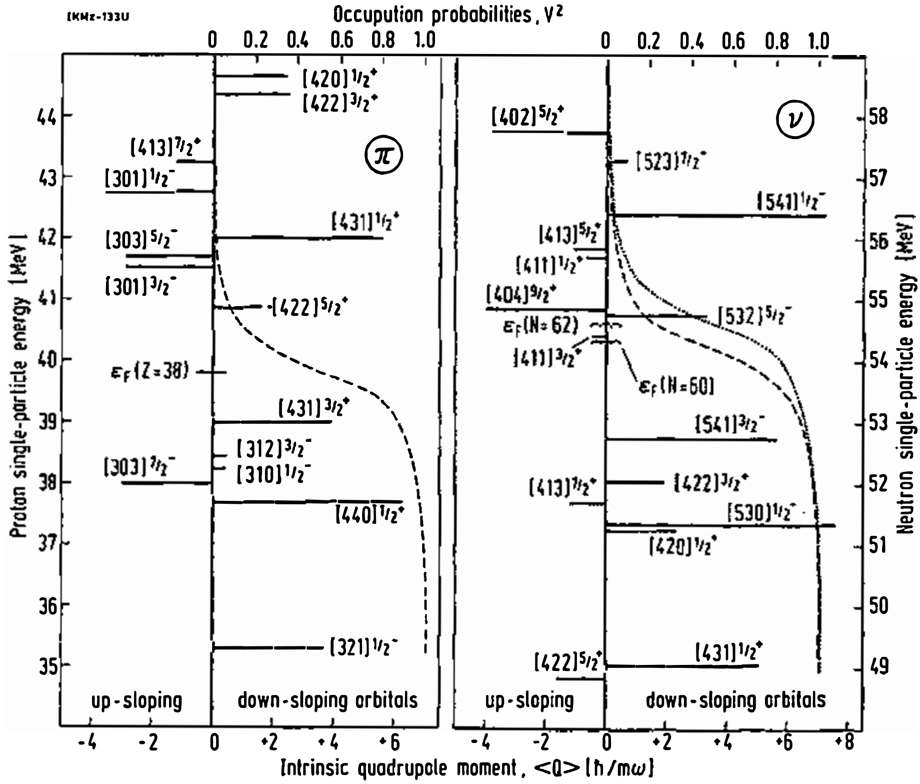

Fig. 3. The proton and neutron intrinsic quadrupole moments (lower x-axis) occurring in Eq. (3) for the orbitals corresponding to ^{98}Sr and ^{100}Sr at $\beta = 0.40$. The Nilsson single-particle energies (y-axis) and occupation probabilities (upper x-axis) given by the dashed and dotted curves have been calculated using the $\varkappa^{-}$ and μ-parameters of Ref. 18. The Fermi level for $Z = 38$, $N = 60$ and 62 is indicated by ε_F.

and 62) Nilsson single-particle states with their energies and occupation probabilities, the intrinsic quadrupole moments $\langle \Omega | \sqrt{16\pi/5} | Y_{20} \Omega \rangle$ for excitations at deformation $\beta = 0.40$ are given. In our calculations, the pairing strength was taken as

$$G_n = \{19.0 - 7.4\,(N - Z)/A\}/A \qquad (1)$$

and

$$G_p = 19.0/A \qquad (2)$$

which reproduces quite well odd-even mass differences in the $A \approx 100$ region. The main contributions to the binding energy are expected from protons in the down-sloping $\Omega = 1/2^+$, $3/2^+$ orbitals of $1g_{9/2}$ parentage and neutrons in the $\Omega = 1/2^-$, $3/2^-$ orbitals of $1h_{11/2}$ origin. Another large contribution comes from the nearly fully occupied [431] $1/2^+$ orbit of n $(2d_{5/2})$ parentage. Contributions from the next higher shells, e. g. protons in the $\Omega = 1/2^+$ orbital of $1g_{7/2}$ origin and neutrons in the $\Omega = 1/2^-$ orbital of $2f_{7/2}$ origin, are relatively small due to low occupation amplitudes.

The expectation value[18] of the p-n quadrupole interaction can be obtained by evaluating the quantity...

$$S_{pn} = -4C \sum_{\Omega_p^i \Omega_n^j} Q_p(\Omega^i)\, Q_n(\Omega^j)\, V^2_{\Omega_p^i}\, V^2_{\Omega_n^j} \qquad (3)$$

where $C = -0.08$ [MeV] (Ref. 16) is the interaction strength, Ω is the projection of the angular momentum on the symmetry axis, $Q_p(\Omega^i)$ and $Q_n(\Omega^j)$ are the intrinsic quadrupole moments of a proton in the Ω_p^i or a neutron in the Ω_n^j orbitals, and the V^2 factors are the BCS occupation probabilities. S_{pn} values of 68, 66 and 67 [MeV $(\hbar/m\omega)^2$] for ^{98}Sr, ^{100}Sr and ^{102}Sr, respectively, have been obtained from Eq. (3) by summing the contributions from protons above the [312] $5/2^-$ orbit and from neutrons beyond the [422] $5/2^+$ orbital at $\beta = 0.40$. These values again clearly demonstate the saturation of the p-n quadrupole interaction already at the onset of deformation in ^{98}Sr. It is interesting to note in this context that the contribution associated with the $1h_{11/2}$ neutrons increases with neutron number from 69% ($^{98}Sr_{60}$) over 76% ($^{100}Sr_{62}$) to 82% ($^{102}Sr_{64}$) of the sum of S_{pn}. This trend is compensated by a simultaneous decrease of the contributions from the even-parity neutron orbitals of $2d_{5/2}$, $3s_{1/2}$ and $1g_{7/2}$ parentage.

In summary, we conclude from our results that the rather unique situation in the Sr isotopic chain with a saturation of strong quadrupole deformation already at its onset, which is clearly reflected by the »twin« character of $^{98}Sr_{60}$ and $^{100}Sr_{62}$, arises from the simultaneous sharp increase in the occupation of down-sloping low-Ω Nilsson orbitals of p $(1g_{9/2})$ and n $(1h_{11/2})$ parentage. In order to get further insight into the specific shell structure of nuclei around $Z = 38$, $N = 60$ it is foreseen to extend our studies to $^{101,102}Sr_{63,64}$ and $^{95-97}Rb_{58-60}$ from β-decay of their Rb and Kr parent isotopes.

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ZASIĆENJE DEFORMACIJE NA $N = 60$ u Sr IZOTOPIMA

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Parametar deformacije jezgre ^{100}Sr dobijen je pomoću vremena života 2^+ stanja. Ta vrijednost je približno jednaka nedavno određenim β parametrima za ^{98}Sr i ^{99}Sr, što je indikacija da se zasićenje deformacije za Sr izotope pojavilo prije sredine neutronske ljuske.