Low-Spin States From Decay Studies in the Mass 80 Region

1. Introduction

There is now extensive experimental evidence for large prolate deformation in the neutron-deficient Rb, Sr, and Y nuclei. For the even-even Sr isotopes, the evidence is based on experimental quadrupole moments extracted from level lifetimes [1,2] and excitation energies of the first excited yrast states [3]. In all these neutron-deficient nuclei, the underlying cause of the prolate deformation has been attributed to the population of strongly polarizing orbitals originating from the $d_{5/2}$ and/or intruder $g_{9/2}$ subshells and large gaps in the single-particle level energies.

The evolution of shapes of mass 80 nuclei from near-spherical to $\gamma$-soft and to well-deformed shapes as function of particle number and angular momentum has been investigated using different theoretical approaches [4-6]. In some cases, shape coexistence interpretations have been invoked to describe irregularities of the moments of inertia of some neutron-deficient even-even Se, Kr, and Sr nuclei at low spins [7]. For the even-even Sr isotopes the situation is quite complicated. Large prolate deformations as observed for $^{76,78}$Sr are in agreement with most of the recent calculations while the nucleus $^{80}$Sr is predicted to be spherical in the ground state with $\beta_2 = 0.053$ [6]. The ground-state deformation of $\beta_2 = 0.4$ as deduced from in-beam $\gamma$-ray experiments [1,2] is in contrast to recent results from fast beam laser spectroscopy [8] where the deduced mean charge radii indicate somewhat less deformed shapes for $^{76,80}$Sr. The neutron-deficient even-even Sr isotopes exhibit yrast level sequences (or moments of inertia) at low spins which show large deviations from the behavior expected for a rigid rotor, possibly indicating shape fluctuations. Thus, the issue of the rigidity of the shapes and the occurrence of co-existing configurations are not yet

Neutron-deficient nuclei in the mass 80 region are known to exhibit strongly deformed ground states deduced mainly from yrast-state properties measured in-beam via heavy-ion fusion-evaporation reactions. Vibrational excitations and non-yrast states as well as their interplay with the observed rotational collectivity have been less studied to date within this mass region. Thus, several $\beta$-decay experiments have been performed to populate low-spin states in the neutron-deficient $^{80,84}$Y and $^{80,84}$Sr nuclei. An overview of excited $0^+$ states in Sr and Kr nuclei is given and conclusions about shape evolution at low-spins are presented. In general, the non-yrast states in even-even Sr nuclei show mainly vibration-like collectivity which evolves to rotational behavior with increasing spin and decreasing neutron number.

Key words: low-spin states; neutron deficient nuclei; prolate deformation.

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resolved and have not been thoroughly addressed as many of the key states of interest are of low spins and of non-yrast nature, i.e., they are not well populated in the heavy-ion fusion reactions usually used for the in-beam studies.

Properties of nuclei along the \( N = Z \) line are also of interest for the astrophysically relevant rapid proton capture (rp) process [9] which is thought to be one of the dominant energy sources in cataclysmic binaries like novae and x-ray bursts. The rp process is characterized by a sequence of fast proton capture reactions and subsequent \( \beta \) decay. Usually, the \( \beta \) decay is slow compared to the fast proton capture reactions. Waiting points can develop where the proton capture is compensated by inverse photo-disintegration or where single proton capture is inhibited at the proton-drip line. The lifetimes of these waiting-point nuclei are determined by the \( \beta \) decay of the ground state or thermally excited states. Thus lifetimes of ground states and/or \( \beta \)-decaying isomeric states in the vicinity of the proton-drip line are important input parameters for calculations of nuclear synthesis, luminosity, and time scale [10]. Nucleosynthesis at the extreme temperature and density conditions associated with such events may well proceed beyond the doubly-magic \(^{56}\text{Ni} \) [11].

Only few alternative probes are available for investigating non-yrast states in nuclei far from stability. The most useful is the careful investigation of the \( \beta \) decay from a higher-\( Z \) parent nucleus. The parent spins are usually low so a large number of non-yrast states is expected to be populated when the decay energy is large. For a successful \( \beta \)-decay experiment sufficient production of the parent nuclei is needed. Far from stability, this is experimentally difficult as production cross section are small and the nuclei are short-lived.

2. Low-Lying Isomers in the Odd-Odd \(^{80,84}\text{Y} \) Isotopes

2.1 New Isomer in \(^{80}\text{Y} \)

A new \( \beta \)-decay experiment has been performed to study the low-spin structure of the \( N = Z + 2 \) nucleus \(^{80}\text{Y} \). The \(^{80}\text{Y} \) source has been produced via the fusion-evaporation reaction \(^{58}\text{Mg}^{(34}\text{Ni},\text{pn}) \) reaction at 190 MeV. The use of inverse kinematics provided a strongly forward-peaked recoil spectrum best suitable for an efficient collection and subsequent separation by the Argonne fragment mass analyzer [12]. The \( A = 80 \) mass separated recoils were implanted on a plastic tape and transported to a \( \beta \)- and \( \gamma \)-ray counter station consisting of three Ge detectors and a low-energy photon spectrometer. Each \( \gamma \)-ray detector had a thin plastic scintillator in front for the detection of \( \beta \) rays. The recoils were implanted within a deposition time of 20 s and their radioactive decay was subsequently measured for 20 s. Several cycles were also performed with 60 s deposition time and 60 s counting time. More experimental details have been reported in Ref. [13].

A single \( \gamma \)-ray spectrum recorded with the low-energy photon spectrometer and representative for the decay of the short-lived mass 80 recoils is displayed in Fig. 1. The strongest \( \gamma \)-ray peak has been identified as the \( 2^+ \rightarrow 0^+ \) transition in \(^{80}\text{Sr} \). Further, a new \( \gamma \)-ray transition at 228.5 keV has been found [13] which is the second strongest line in the spectrum. This transition depopulates a new isomer in \(^{80}\text{Y} \) with a half-life of 4.7(3) s [13]. Spin and parity of the isomer has been determined to be \( 1^+ \). Thus, the isomer decays by a M3 transition to the \( 4^+ \) ground state. The extracted M3 transition strength is 0.78(5) Weisskopf units. Most interestingly, the isomer undergoes \( \beta \) decay as well to low-lying states in \(^{80}\text{Sr} \) [14], as can be seen in the decay scheme of the isomer given in Fig. 2, upper left-hand side. This conclusion has been drawn from two experimental facts: (i) The time distribution of the \( 2^+ \rightarrow 0^+ \) 385.9 keV transition in \(^{80}\text{Sr} \) does not show the expected delayed feeding by the 228.5 keV isomeric transition (as the \( 4^+ \rightarrow 2^+ \) 594.8 keV transition does), i.e., the time distribution can be fitted well with a single exponential decay curve. This indicates that the delayed component is canceled out. (ii) The difference spectrum between early and late time correlated events exhibits a strong 385.9 keV transition. This spectrum is shown in Fig. 3. The spectrum has been generated by subtracting the time-\( \gamma \) events of the 15 s to 60 s time range (late events) from the time-\( \gamma \) events of the 0 s to 10 s range (early events). Further, events in the time range 10 to 15 s have been excluded (see inset of Fig. 3). For normalization, we assumed that the intensity of the 783.1 keV line depopulating the 6\(^+ \) state at 1763.7 keV in \(^{80}\text{Sr} \) cancels out leading to a factor of 0.68. As a result a small intensity amount of the 594.8 keV line remains in the difference spectrum. This may indicate that the \( 1^- \) isomeric \( \beta \) decay is highly fragmented. The situation is similar to the \( 1^- \) ground-state \( \beta \) decay of \(^{80}\text{Rb} \) [15]. The difference spectrum indicates, in addition to the strong 385.9 keV transition, a weak 1350.4 keV line. The same 1350.4 keV transition can be seen in the sum coincidence spectrum of the 756 and 1142 keV gates providing evidence for a level at 2492.5 keV. This level seems to be populated in the isomeric decay only and has probably a low spin.

The \( \beta \)-decay branch has been estimated to be about 19\( (2) \)%. This result has important consequences for calculations of the rp-process nucleosynthesis of \(^{80}\text{Kr} \)
since the longer lived ground state of $^{80}$Y ($T_{1/2} = 30.1(5)$ s [13]) is partly bypassed by the isomeric $\beta$ decay, and a shorter effective half-life of $^{80}$Y is obtained which leads to a reduction of the calculated overproduction of $^{80}$Kr [10].

Total Routhian surface calculations [4] have shown that the odd-odd nucleus $^{80}$Y exhibits a strongly deformed prolate shape with a quadrupole deformation of $\beta_2 = 0.37$ for the ground state. The prolate minimum persists up to high rotational frequencies. Thus, the deformed shape inspired the application of two-quasiparticle-plus-rotor calculations to investigate the wave functions of the low-lying states in terms of Nilsson orbitals. We found that the low-spin structure can be well explained if a proton-neutron residual interaction is employed. In this case the ordering of the states and the energy splitting between the 4$^-$ ground state and the 1$^-$ isomer can be well reproduced. The wave functions contain mainly the proton [422]5/2$^+$ and the neutron [301]3/2$^-$ Nilsson orbitals. These orbitals are coupled parallel and antiparallel in the 4$^-$ ground state and in the 1$^-$ isomer of $^{80}$Y, respectively. The model calculations demonstrate that the deformed picture accounts very well for the observed properties of the low-lying states in $^{80}$Y.

2.2 Low-Spin States in $^{84}$Y

Early evidence was presented that the odd-odd nucleus $^{84}$Y has very likely an 1$^+$ ground state and a higher-lying (5$^+$) isomer at an energy of about 500 keV [16,17]. This structure was deduced from early decay studies and the excitation energy of the isomer was an estimate only. Also, a few $\gamma$ rays had been previously assigned to the $^{84}$Zr decay [18], however, not placed into a level scheme. Therefore, three new decay experiments have been carried out: (i) via the irradiation of a $^{58}$Ni target with $^{28}$Si ions at 97 MeV using a modified NORDBALL setup [19], (ii) via the irradiation of a $^{58}$Ni target with 99 MeV $^{28}$Si ions and (iii) via the irradiation of a $^{58}$Ni target with 135 MeV $^{32}$S ions [20]. The latter two experiments were performed at Florida State University. In the first two experiments the chosen target-projectile combinations ensured that the even-even nucleus $^{84}$Zr was produced in-beam, without any in-beam population of states in $^{84}$Y and $^{84}$Sr. In this way all states seen in these two latter nuclei were populated via the $\beta$-decay chain $^{84}$Zr $\rightarrow$ $^{84}$Y $\rightarrow$ $^{84}$Sr only. The experiments at Florida State University were carried out with 5 Ge detectors and a low-energy photon spectrometer to detect the $\gamma$ rays.
Fig. 2. Level scheme of $^{80}$Sr deduced from the $\beta$ decay of $^{80}$Y. The figure has been taken from Ref. [14].

It has been found that the 1+ isomer in $^{84}$Y has an excitation energy of 67 keV and undergoes $\beta$ decay only. No low-energy 67 keV $\gamma$ transition to the ground state in $^{84}$Y has been seen in the singles spectrum measured with the low-energy photon spectrometer. A partial decay scheme is shown in Fig. 4 where emphasis has been placed on the low-spin structure in $^{84}$Y and the population of the 0+ states in $^{84}$Sr by the $\beta$ decay of the 1+ isomer. Further, states up to (7+) in the yrast $\gamma$-vibrational band of $^{84}$Sr have been identified giving evidence for a possible spin and parity assignment of 6+ to the ground state of $^{84}$Y, in contrast to the previous assignment of (5+) [17].

The new decay data revealed many new $\gamma$ rays in $^{84}$Y and $^{84}$Sr and hence many new levels have been identified in both nuclei. For example, the previously reported excited 0+ states at 1505 and 2075 keV in $^{84}$Sr as identified via a (p,t) reaction [21] have been observed via $\gamma$-ray spectroscopy at 1504 and 2072 keV, respectively, for the first time. These states depopulate via 711 and 1279 keV transitions to the first excited 2+ state at 793 keV in $^{84}$Sr. An intense 793 keV peak has been seen only in the coincidence gates at 711 and 1279 keV indicating a very low multiplicity. Thus the origin is very likely a low-spin state in $^{84}$Y, i.e., the $\beta$ decay of the 1+ isomer. The number of coincidence events of the 1279 keV line gated by the 793 keV transition in the 10 different detector-pair matrices of experiment (iii) was good enough to deduced angular correlation coefficients [22]. They provide evidence for a 0+ → 2+ → 0+ decay sequence.

3. Low-Lying States in Even-Even Neutron-Deficient Sr and Kr Isotopes

3.1 Excited 0+ States in Sr Isotopes

The evolution of the nuclear shape from spherical to deformed in the even-even Sr isotopes is well known when moving away from the neutron shell closure at N = 50. These findings are based mainly on yrast level properties investigated via heavy-ion fusion-evaporation reactions. The study of non-yrast low-lying states may provide additional evidence to support these claims, or may indicate a more complex nuclear structure at low spins. The careful study of the $\beta$ decay of odd-odd Y
study of the $\beta$ decay of odd-odd Y nuclei seems to be the best method for populating non-yrast levels in neutron-deficient even-even Sr isotopes. Thus, the experiment described before for the investigation of an isomer in $^{80}\text{Y}$ has been analyzed for the $^{80}\text{Y} \rightarrow ^{80}\text{Sr}$ $\beta$ decay as well. The high selectivity of the Argonne fragment mass analyzer and the use of a multi-detector setup provided clean data. The known $^{80}\text{Sr}$ level scheme could be extended by 14 new levels [14], see Fig. 2. Spin and parity assignments are given based on the observed feeding and depopulation pattern, deduced log $ft$ values, and on a comparison with the decay of the $^{78}\text{Rb}$ 4$^-$ isomer to low-lying states in $^{78}\text{Kr}$ [23].

Most of the known excited 0$^+$ states in mass 80 nuclei have been identified via radioactive decay studies or particle-transfer reactions. The experimental detection is sometimes difficult since a 0$^+_2 \rightarrow 0^+$ E0 transition can be verified only via a conversion electron measurement. Using $\gamma$-ray spectroscopy, usually the $0^+_2 \rightarrow 2^+$ E2 transition is detected. In general, the E0 matrix elements depend sensitively on the nuclear charge distribution and thus on the nuclear deformation [24]. Hence, the identification of these excited 0$^+$ states in a chain of isotopes allows to study the evolution of the nuclear shape at low spins. The latest results for the even-even Sr isotopes ($Z = 38$) are displayed in Fig. 5. The previously reported 0$^+$ states in $^{84}\text{Sr}$, detected via particle-transfer reactions and confirmed by present $\gamma$-ray spectroscopy, are included. With decreasing neutron number, the position of the excited 0$^+$ states decreases as well and a multiplet-like grouping of the levels is obtained.

### 3.2 Excited 0$^+$ States in Kr Isotopes and N = 38 Isotones

The systematics of the excited 0$^+$ states in the neutron-deficient even-even Kr isotopes is plotted in Fig. 6. The recently discovered low-lying 0$^+_2$ state in $^{74}\text{Kr}$, at most 85 keV above the first excited 2$^+$ state at 456 keV [25], refines the previously suggested shape coexistence picture [26]. This picture of a deformed-spherical shape coexistence was invoked to explain the irregularities in the energy spacings (or moments of inertias) of the lowest yrast excitations in the even-even $^{74,76}\text{Kr}$ nuclei. Now an oblate shape is suggested for the excited 0$^+$ state in $^{74}\text{Kr}$, in contrast to the prolate deformed ground-state band. The half-life reported for the 0$^+_2$ in $^{74}\text{Kr}$ is the partial time for the E0 transition. The low-energy $\gamma$-ray decay has not been found yet.
3.3 Vibration-Like Multiplets in Even-Even Sr Nuclei

As can be seen in Fig. 8, the new level scheme of $^{80}$Sr deduced from our $\beta$-decay study is clustered into states typical of one-, two-, and three-phonon multiplets of an anharmonic vibrational nucleus. In this approach the lowest $2^+$ state at 385.9 keV can be interpreted as an one-phonon vibrational state. States corresponding to the two-phonon triplet may be the observed states with spins $2^+_2$ and $4^+_1$ at energies of 1142.1 and 980.7 keV, respectively. From theoretical considerations there should also be a $0^+$ state to complete the two-phonon triplet. A $0^+$ level at 1.0 MeV was observed in a $^{78}$Kr($^3$He,$n$)$^{80}$Sr reaction study [29] but this level has not been seen in our decay data set. Based on a phenomenological parametrization of the effective interaction between phonons [30,31] and using experimental values for the interaction parameters as deduced from members of the observed three-phonon multiplet, a range of 820 keV to 880 keV can be estimated for the excitation energy of the two-phonon $0^+$ state. For three phonons, the expected multiplet of levels consists of $0^+_3$, $2^+_3$, $3^+_2$, $4^+_2$, and $6^+_1$. There are observed states with $2^+_3$, $3^+_2$, $4^+_2$, and $6^+_1$ at 1653.6 keV, 1571.0 keV, 1832.5 keV, and 1763.7 keV, respectively, which might be identified with these excitations. The expected $0^+_3$ level has not been seen. Similar to the estimate of the excitation energy of the $0^+_2$ state, an energy range of 1890 keV to 2270 keV can be deduced for the third $0^+$ state based on the anharmonicity of the $2^+_2$ state.

The observed vibrations in $^{80}$Sr are clearly anharmonic since the $(2I + 1)$ weighted energy centroids of the known members of the multiplets are at 1036 keV and 1726 keV for $n = 2$ and 3, respectively, i.e., the higher orders (with $n = 2, 3$) are not strictly a multiple of the one-phonon energy of 386 keV. The deviations from the expected energies for a harmonic vibrator can be attributed to various anharmonic effects. One such anharmonicity may arise from a finite quadrupole deformation or angular momentum dependence of the nuclear shape. Much less anharmonicity is needed to understand the low-lying states in $^{84}$Sr, as can be seen on the right-hand side of Fig. 8. In particular, the observed $0^+$ states fit very well into this interpretation and complete the multiplets. The energy centroids of the $n = 2, 3$ multiplets are almost a multiple of the 793 keV ($n = 1$) energy. Thus, an almost harmonic vibration-like nature in $^{80}$Sr is deduced.

Fig. 4. Selected low-lying states in odd-odd $^{84}$Y and even-even $^{84}$Sr observed in $\beta$ decay via the chain $^{84}$Zr $\rightarrow ^{84}$Y $\rightarrow ^{84}$Sr using five Ge detectors and a low-energy photon spectrometer. The experimental results have been taken from Refs. [19,20].

It should be pointed out that the second $0^+$ state in $^{74}$Kr fits quite well into the $N = 38$ systematics as can be seen in Fig. 7. In most of these isotones, an excited $0^+$ state has been found which decays by a low-energy $\gamma$ ray to the first $2^+$ state. The deduced $0^+_2 \rightarrow 2^+$ E2 transition strengths are in the order of 45 Weisskopf units indicating substantial collectivity. The reported E0 matrix elements are also given in the figure.
Position of excited $0^+$

Even-Even Sr, $Z = 38$

Fig. 5. Excited $0^+$ states and the lowest yrast excitations are displayed for even-even neutron-deficient Sr isotopes. The experimental results on the $0^+$ states have been taken from: $^{80}$Sr, Ref. [29]; $^{82}$Sr, Ref. [17]; $^{84}$Sr, Refs. [20,21]; $^{86}$Sr, Ref. [21].

Position of excited $0^+$

Even-Even Kr, $Z = 36$

Fig. 6. Excited $0^+$ states and the lowest yrast excitations are displayed for even-even neutron-deficient Kr isotopes. The experimental results on the $0^+$ states have been taken from: $^{72}$Kr, Ref. [25]; $^{74,76,80,82}$Kr, Ref. [17].
Fig. 7. Excited 0+ states in some neutron-deficient \( N = 38 \) isotones. The experimental E2 and E0 transition strengths are given. The data have been taken from: \(^{70}\text{Ge}, \text{Ref. [27]}\); \(^{72}\text{Se}, \text{Ref. [28]}\); \(^{74}\text{Kr}, \text{Ref. [25]}\).

4. Summary and Conclusions

Modern \( \beta \)-decay experiments employing multi-Ge detector and scintillator arrays combined with in-flight mass separation of recoils produced via nuclear reactions provide a very sensitive tool for the investigation of low-spin states in nuclei far off the line of stability. This has been demonstrated by the recent results obtained for the highly-fragmented radioactive decay of \(^{80}\text{Y} \rightarrow ^{80}\text{Sr}\). In general, the new decay data suggest that the low-lying structures of \(^{80,84}\text{Sr}\) show many vibration-like features in a potential with modest deformation including candidates for two- and three-phonon multiplets. This vibration-like nature seems to evolve to a more rotational behavior with increasing angular momentum and decreasing neutron number.
Fig. 8. Low-lying levels in the even-even $^{80,82,84}$Sr isotopes. The level energies indicate the vibration-like multiplet structure. For $^{84}$Sr, the multiple one-phonon energies are given on the right-hand side.

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5. References

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About the authors: J. Döring is research scientist at the Gesellschaft für Schwerionenforschung in Darmstadt, Germany, A. Aprahamian is a professor of physics at the University of Notre Dame, and M. Wiescher is the Friedman Professor of Physics at the University of Notre Dame.