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Levels in ^{102}Zr populated in the decay of ^{102}Y

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The β^- decay of ^{102}Y to levels in ^{102}Zr was investigated from sources produced in the thermal neutron induced fission of ^{235}U and separated using a gas-filled recoil separator. Singles and coincidence γ and x ray measurements were carried out. Only one β decaying level of ^{102}Y was observed with a half-life of 0.36 ± 0.04 s. A total of seven γ transitions was placed in a level scheme consisting of excited states in ^{102}Zr at 152 (2^+), 478 (4^+), 731, 891, 965 (6^+), 1538, and 1823 keV. The results are compared with those from fission fragment studies and a calculation based on a deformed quasiparticle basis. Implications for the systematics of even-even Zr nuclides with mass numbers around 100 are discussed.

RADIOACTIVITY ^{102}Y [from ^{235}U(n,f)]; measured $T_{1/2}$, E_γ, I_γ, $\gamma\gamma$, and $x\gamma$coin, Ge(Li) detectors; ^{102}Zr deduced levels, J, π. Mass and charge separated ^{102}Y activity.

I. INTRODUCTION

The structure of neutron-rich even-even Zr nuclides ($Z=40$) is of great interest, because they show "magic" properties for mass numbers 92, 94, 96, and 98, but between ^{98}Zr and ^{100}Zr a "phase transition" seems to occur in which the energy of the 2_1^+ state drops by a factor of 6 and the E_{4^+}/E_{2^+} ratio rises from 1.67 (magic) to 2.65 (almost rotational). It is of interest to extend the Zr systematics to ^{102}Zr to determine to what extent a rigid rotor type of structure is reached.

The yrast bands for neutron-rich even A Zr nuclides up to $A=102$ have been determined by Cheifetz *et al.*[1] and in part by other authors[2-4] from studies of γ rays emitted by recoiling fission fragments. Jared *et al.*[5] determined the half-lives of the 2_1^+ levels. This is the only information available on the level structure of ^{102}Zr. The structure of ^{98}Zr and ^{100}Zr has been also determined[6,7] by studying the decay of ^{98}Y and ^{100}Y produced by fission of ^{235}U with thermal neutrons. The activity was mass separated using the gas-filled separator JOSEF. In this type of experiment, in addition to the yrast bands, other low-spin excited states are observed.

The existence of ^{102}Y was reported by Grüter *et al.*,[8] who gave only a half-life of about 0.9 s. Klein[9] reported a half-life for ^{102}Y in the range from 0.3 to 0.5 s. This range was determined from the decay curve for the 600-keV γ ray from ^{102}Zr decay assuming the Zr to be derived entirely from the decay of the ^{102}Y parent. Gamma transitions observed in the fission fragment work[1] were not seen by Klein.

The yrast band which was derived from a series of observations of γ rays and conservation electrons from ^{102}Zr primary fission fragments[10-12] was established up to the 6^+ and possibly the 8^+ member, and a value of 3.15 was obtained for the E_{4^+}/E_{2^+} ratio, which is quite close to the rigid rotor limit of 3.33. The existence of a large deformation ($\beta_2=0.38\pm0.02$) was deduced[5] from the half-life of 3.17 ± 0.25 ns for the 2_1^+ level at 152 keV.

The beginning of the shape transition for even A Zr nuclides was investigated by Federman *et al.*,[13] who carried out shell model calculations for ^{96}Zr and ^{98}Zr assuming an inert ^{94}Sr core. Good agreement with the available experimental information was obtained. They pointed out that in their picture the 0_2^+ state which lies at only 331 keV in ^{100}Zr should rise in energy after the deformed shape is achieved in ^{102}Zr.

A calculation of the level structure of ^{102}Zr was carried out by Kumar *et al.*[14] after the establishment of a deformed quasiparticle basis. Positive parity levels up to 3.1 MeV were determined in terms of the parameters β,γ, and the K composition of their wave functions. Most levels fit into bands of mixed K but with one value of K dominating. The authors give values of $\beta=0.409$ and $\gamma=12°$ for the yrast band of ^{102}Zr. The potential energy surface (PES) calculations of Faessler *et al.*[15] resulted in a value of $\beta=0.36$ for ^{102}Zr. It is of special interest that they predict a symmetric deformation ($\gamma=0$) for ^{102}Zr but not for the heavier isotone ^{104}Mo.

Since the nucleus ^{102}Zr cannot be reached in conventional reaction experiments, it is necessary to carry out a study of ^{102}Y decay in order to obtain more complete information on the structure of ^{102}Zr. Separation of ^{102}Y with isotope separation on-line (ISOL) systems is difficult due to its refractory nature and expected half-life. It was then decided to investigate the decay of ^{102}Y using the gas-filled separator JOSEF which separates all fission products (irrespective of their nuclear charge Z) with very short separation times ($\leq 2\ \mu$s), but which has the limitation of poor selectivity which makes the study of a low-yield fission product like ^{102}Y difficult against a background of higher-yield products.

II. EXPERIMENTAL PROCEDURES AND RESULTS

A. Source preparation

The gas filled device JOSEF (Ref. 16) provides a beam of fission products from the ^{235}U(n,f) reaction spatially separated according to mass A and nuclear charge Z. For identical fission products the separation is essentially independent of the different ionic charges and kinetic energies so that a relatively intense beam is available. The resolution is not sufficient to give isotopically pure fission product beams, but the nuclide from which particular γ transitions proceed can be identified by measuring the γ intensity as a function of the magnetic rigidity ($B\rho$) of the gas filled magnet. The position[17] of maximum intensity $(B\rho)_m$ is then compared with calibration curves established from known fission products. Since several nuclides have however, almost the same $(B\rho)_m$, other measurements of half-life and $\gamma\gamma$ and γx coincidences were needed to unambiguously assign γ transitions to particular nuclides. Details of these techniques have been described elsewhere.[18] The gas filling used for this experiment at JOSEF was 4 Torr He.

B. γ ray measurements and identification of ^{102}Y

The first search[19] for ^{102}Y activity was undertaken, in which the activities were carried to an off-line counting position using an air jet. Evidence for ^{102}Y was not so clear, indicating that its half-life was shorter than 0.9 s and/or its yield was low. The 152-keV γ ray which was suggested to be the $2_1^+ \rightarrow 0_1^+$ in ^{102}Zr was then clearly observed during a γ singles measurement with the γ ray detector in the "in beam" position of JOSEF. In order to confirm the assignment of the 152-keV γ ray to ^{102}Y decay, the $B\rho$ measurements were carried out in beam with a 30 cm^3 intrinsic Ge detector with an energy resolution of 0.7 keV for the 122-keV γ ray from ^{57}Co. The fission product beam was stopped by a 10 cm wide tape in a moving tape collector that periodically removed the long-lived activities. The measuring time at each $b\rho$ value was 4 h and the measurement encompassed 17 $B\rho$ values. The data were accumulated on the computer analyzer MECCA.[20]

The $B\rho$ distributions for the 151.9-, 326.6-, and 579.4-keV γ rays are shown in Fig. 1(a). The experimental situation was complicated by the fact that three closely spaced γ rays are present in the spectra around 150 keV: the 150.5-keV transition from the decay[21] of ^{103}Zr, the 151.9-keV line from ^{102}Y, and the 152.9-keV line from ^{102}Zr.[21] Moreover, ^{102}Y and ^{103}Zr have the same $(B\rho)_m$ position, which is well separated from that of ^{102}Zr in Fig. 1. The $B\rho$-calibration lines and $(B\rho)_m$ position for ^{102}Y are shown in Fig. 1(b).

An example of the singles spectra measured with a 61 cm^3 Ge(Li) detector with a resolution of 2.2 keV at 1.3 MeV is shown in Fig. 2. Due to the low yield only five γ lines from ^{102}Y decay were observed directly in singles measurements. An energy calibration was carried out using ^{152}Eu as a primary standard. These data were used to establish secondary fission product γ ray standards which subsequently provided a calibration for the energies of weak ^{102}Y γ rays from coincidence spectra. The efficiency of the γ ray detectors was determined using ^{152}Eu. Checks for absorption of low-energy γ rays were made using relative intensities[22,23] from isomers in ^{96}Y and ^{97}Zr. The energies, intensities, and placements of γ rays assigned to ^{102}Y decay are given in Table I.

C. Half-life measurements

The half-life of ^{102}Y was measured using the intrinsic Ge detector. In this experiment the activity was collected periodically for 0.6 s. At the end of the collection period the fission product beam from JOSEF was turned off by imposing a positive potential on the electrostatic fission product guide at the

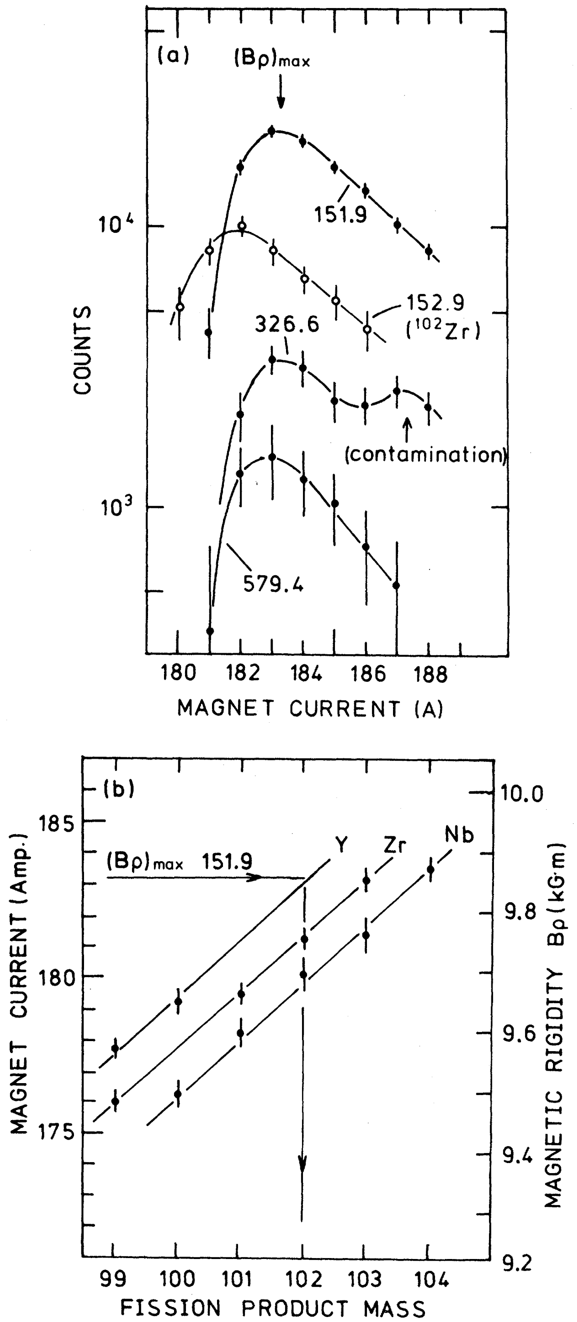

FIG. 1. (a) $B\rho$ distributions for some of the γ rays assigned to the decay of ^{102}Y. (b) Dispersion curves for JOSEF and the assignment of the 151.9 keV line to ^{102}Y.

exit of JOSEF (Ref. 16) to chop the beam. Next the decay was measured for 2.2 s. Finally the long-lived activities were removed by moving the tape and the cycle was repeated. The analyzer was operated in a multiscaling mode of 0.04 s per channel. During the run the dead time was monitored by both a pulser and the 662-keV γ ray from ^{137}Cs. Counts were accumulated for 86 h and spectra were added in units of two spectra to improve statistical accuracy. Correction for leakage during the "off" period of the separator beam was proven to be unnecessary by observing the intensity of the γ rays from μs isomers. During deflection the beam intensity was suppressed by a factor of 10^2, as can be seen in Fig. 3.

A decay curve for the 152-keV γ ray is shown in Fig. 4. Inset (a) in the figure shows the 152-keV triplet just after the beam had been chopped and inset (b) shows that ^{102}Y had almost completely decayed by the end of the measuring cycle. A least-squares fit to the data assuming only one half-life gives $T_{1/2}=0.36\pm0.04$ s for ^{102}Y decay. This value is consistent with the range of from 0.3 to 0.5 s reported by Klein[9] but is less than the value of 0.9 s obtained earlier.[8] The older measurement was contaminated by the 150.5-keV transition from ^{103}Zr decay which has the same $B\rho$ distribution (see above) and was unknown at that time. A half-life measurement was also carried out off-beam at a position 30 cm away from the point of deposit. Although the intensity of the 152-keV γ ray was very low, a half-life of 0.4 ± 0.1 s was obtained, consistent with the value obtained in beam. The corresponding decay curve in shown in Fig. 4.

Careful analysis of the decay curve for the 152-keV transition gave no evidence for a second component due to an isomer in ^{102}Y. This contrasts with the situation in ^{98}Y and ^{100}Y where high- and low-spin isomers with substantially different half-lives are observed.[6,7] The experimental data do not, however, definitely rule out the existence of an isomeric state in ^{102}Y. Such a state might have escaped detection if it also had a half-life around 0.4 s or if its half-life was significantly different from 0.4 s but was only fed weakly in fission. Also, an isomer that only fed the ground state and excited 0^+ levels in ^{102}Zr [similar to the situation in ^{98}Zr (Ref. 6)] might be hard to detect. Unfortunately the weak source strength did not allow the determination of the decay curves for the weaker γ rays in ^{102}Zr.

D. Coincidence measurements

Two sets of coincidence measurements were carried out at the in-beam position of JOSEF. For one set, the 30 cm^3 Ge detector and a 61 cm^3 Ge(Li) detector was used. The energy range covered was from the Y x rays to 1 MeV for the 30 cm^3 detector and 30 keV to 2 MeV for the 61 cm^3 detector. The two detectors were positioned at a relative angle of about 70° and about 3 cm away from the fission product activity. The tape system was operated in a

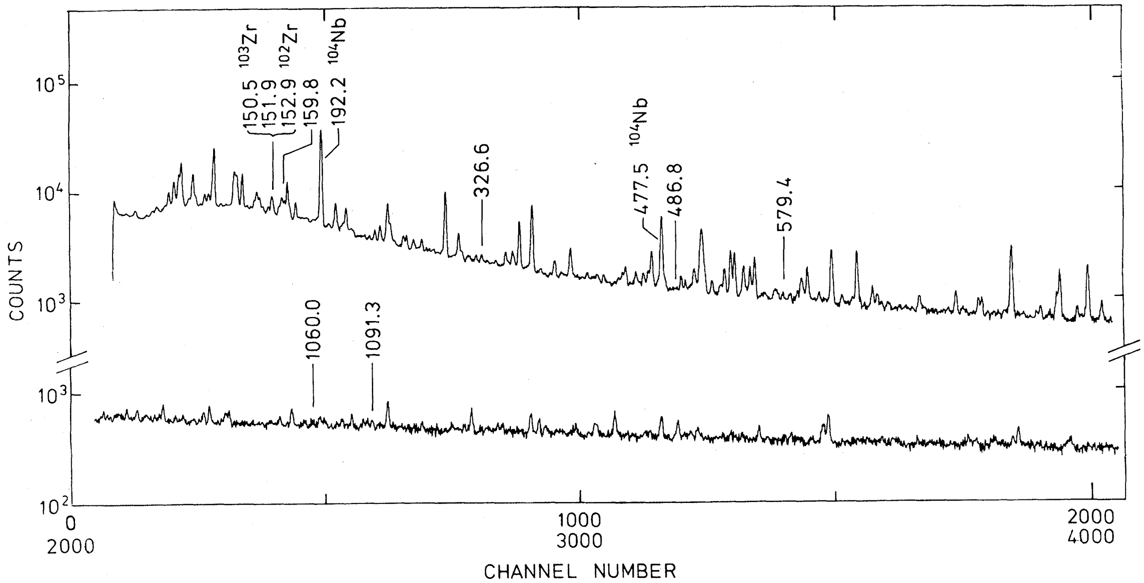

FIG. 2. Singles spectrum measured with the 61 cm^3 Ge(Li) detector, at $B\rho$=9.85 kGm. The energies of γ rays assigned to the decay of ^{102}Y are given in keV.

cycle of 2 s collection with a 0.4 s transport time. Two energy and one time-to-amplitude converter (TAC) output signals for each event were recorded on a magnetic tape in list mode. The TAC time spectrum had a FWHM of 17 ns. Events were accumulated for 10 d.

For the second γ-γ coincidence run, the 61 cm^3 detector and a 150 cm^3 Ge(Li) detector with a resolution of 2.0 keV at 1.3 MeV were used. The energy range was 30 keV to 1.6 MeV for both detectors. Events were accumulated for 4 d. Coincidence spectra were extracted by setting a time gate (60 ns wide) on the TAC spectrum and energy gates on each of the relevant peaks in the global coincidence spectra for the 30 cm^3 detector and the 61 cm^3 detector. Compton background was subtracted from the coincidence spectra. Similar analyses were carried out with energy gates on the global spectra of the 61 cm^3 and 150 cm^3 detectors. Some gated spectra from the x-γ and γ-γ coincidence measurements are shown in Figs. 5 and 6, respectively. The results of the coincidence measurements are summarized in Table II.

TABLE I. γ transitions observed in ^{102}Y decay.

E_γ (keV)	I_γ^a	Placement (keV)
151.9±0.1	100±4[b]	152−0
159.8±0.1	9±3[c]	891−731
326.6±0.1	43±6[b]	478−152
486.8±0.2	7±3[c]	965−478
579.4±0.2	46±10[b]	731−152
1060.0±0.3	13±7[c]	1538−478
1091.3±0.3	39±8[c]	1823−731

[a]Intensities normalized to 100 for the 152-keV γ ray.
[b]Intensity determined from singles γ ray spectrum.
[c]Intensity determined from coincidence spectrum gated on the 152-keV γ ray.

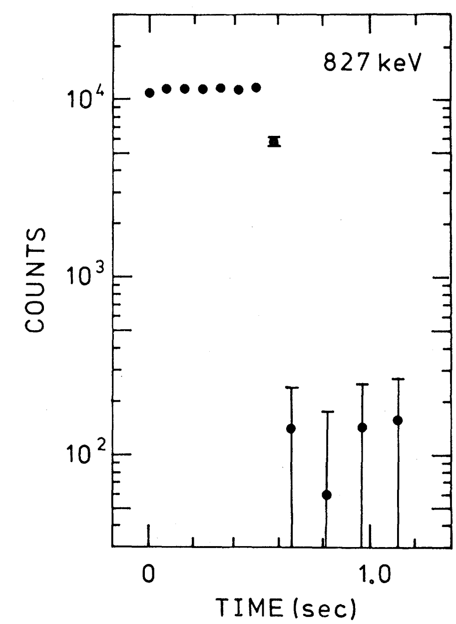

FIG. 3. Example of the suppression of the fission product beam with the electrostatic deflector when a positive voltage of 5 kV is applied to the wire of the fission product guide. The γ transition of 827 keV is emitted in the depopulation of a μs isomer in ^{95}Y. The large uncertainties in the intensities after shutoff of the beam were due to background subtraction.

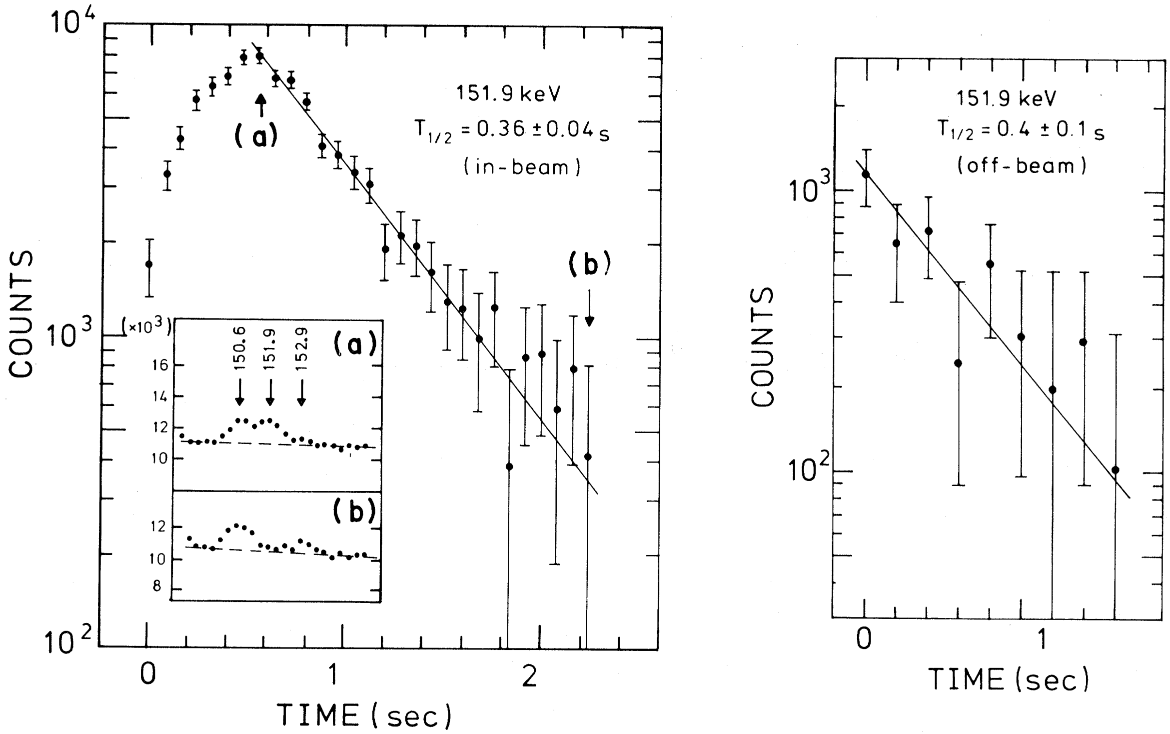

FIG. 4. Intensity versus time distribution for the 151.9 keV γ ray emitted in the decay of ^{102}Y. The inset shows that the 151.9 keV line has essentially decayed 2.08 s after the end of fission product deposition.

III. DECAY SCHEME AND DISCUSSION

A. Construction of the ^{102}Y decay scheme

The measured γ ray energies and intensities and coincidence relationships were used to construct the decay scheme for ^{102}Y shown in Fig. 7. The isotopic assignment is based on the $B\rho$ measurements discussed above and the good agreement of our level energies of 2_1^+ (151.9 keV), 4_1^+ (478.5 keV), and 6_1^+ (965.3 keV) with the corresponding values of 151.9, 478.5, and 964.5 keV obtained in the fission fragment studies.[1] In turn, our measurements support the assignment of the above-mentioned yrast band to ^{102}Zr. Also the coincidences between several γ rays from ^{102}Y decay and the Zr $K\,\alpha_1$ x ray confirm the Z assignment. The half-life of 0.36±0.04 s for ^{102}Y measured in this work is considerably shorter than the range of 0.9 to 2 s predicted by the "gross theory of β decay."[24] The same trend also holds for the half-lives[6,7] of ^{98}Y and ^{100}Y so that the predictions for neutron-rich even A Y nuclides are systematically too long.

A definite coincidence was observed between relatively strong γ rays at 579 and 1091 keV with intensities of 46±10 and 39±8, respectively. Both are in coincidence with the 152-keV γ ray establishing a level at 1822.6 keV. It is difficult to determine the order of the above two γ rays on the basis of an intensity alone, but based on systematics, as discussed below, we favor a placement with a level at 731.3 keV.

A γ ray at 159.8 keV observed in coincidence with the 152- and 579-keV γ rays establishes a level at 891.0 keV which further supports the ordering of the 579-1091-keV cascade since the 160-keV γ ray is not in coincidence with the 1091-keV transition. In a preliminary level scheme[25] the 1091 keV line was placed on top of the 152-keV level, but the 160-keV transition was not known at that time. Finally the level postulated at 1538.5 keV is based on coincidences between the 1060- and 327-keV γ rays.

We have not calculated β^- feedings and logft values for the various ^{102}Zr levels. We take this conservative approach due to the difficulty of identifying ground-state γ transitions in the JOSEF singles spectra and the fact that both low and high spin levels seem to be populated in β^- decay (see below), indicating the possible existence of more than one β-decaying state in ^{102}Y.

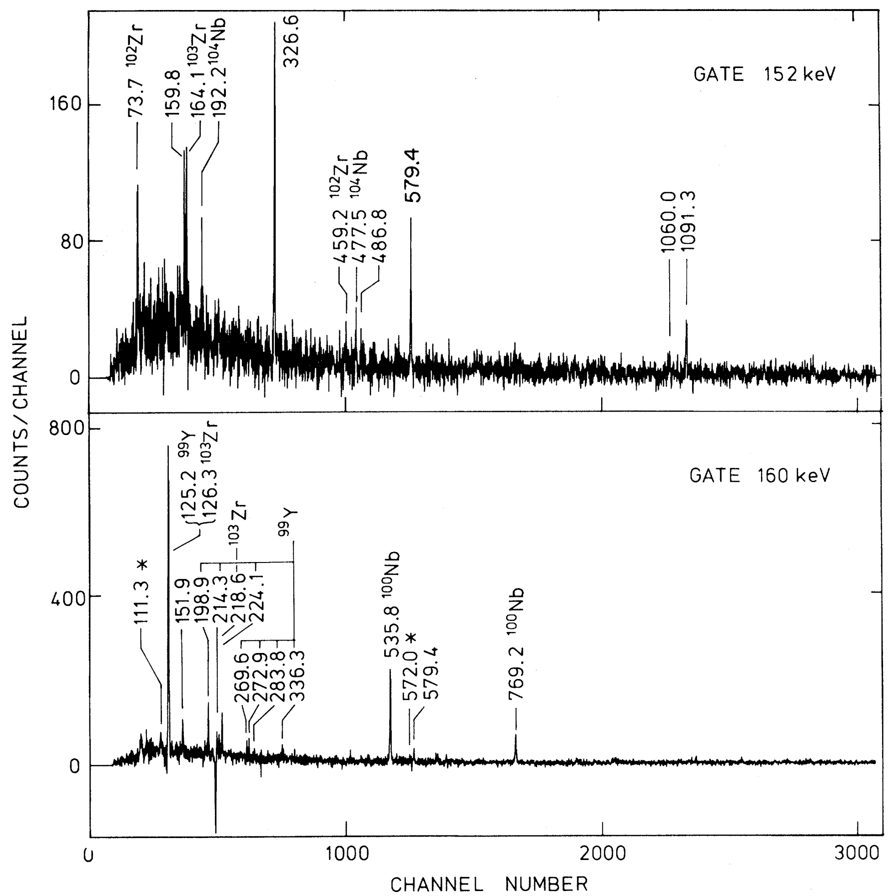

FIG. 5. Examples of the coincidence spectra for ^{102}Zr for low energy γ-ray gates. The spectra were measured with the 61 cm^3 Ge(Li) detector. The gates were set on the spectra of the 30 cm^3 intrinsic Ge detector. The known γ rays which appeared in the same gate as contamination are labeled with the parent isotopes. An asterisk indicates unassigned γ rays.

B. Systematics and comparison with theory

The level scheme for ^{102}Zr determined in this work is compared with the level structure for lighter neutron-rich even-even Zr nuclides in Fig. 8. The 2_1^+ state decreases from 1751 keV in ^{96}Zr to 152 keV in ^{102}Zr, indicating a fairly rapid transition from a "magic" to a rigid rotor configuration, and the ratio E_{4^+}/E_{2^+} rises to 3.15 almost at the rigid rotor limit of 3.33. This value is among the highest in the region around $A=100$ and is only exceeded by the ratio[26] of 3.23 for ^{100}Sr.

Another feature of the systematics is the lowering of the 0_2^+ state to a minimum of 331 keV at ^{100}Zr. Federman et al.[13] predicted that as deformation increases with the addition of neutron pairs, the 0_2^+ state should reach a minimum in the transition region (^{100}Zr) and then rise again (^{102}Zr) as the deformation approaches the rigid rotor limit. We do not observe a 0_2^+ state below 500 keV, but this could be due to experimental limitations.

In Fig. 7 the level structure of ^{102}Zr determined in this work is compared with the calculation of Kumar et al.[14] The most interesting feature of the new experimental information on ^{102}Zr is the postulation of two levels at 731 and 891 keV. One or both of these levels may correspond to predicted levels[14] at 823 and 840 keV. The 731-keV level is a good candidate for the 0_2^+ state in that it γ decays only to the 2_1^+ level. In addition, the level at 731 keV in ^{102}Zr is primarily fed by a high-lying level at 1823 keV, similar to the situation in ^{100}Zr, where the 0_2^+ level at 331 keV is fed primarily from a high-lying level at 1428 keV. If the above speculation is correct, then the 0_2^+ state has risen from a minimum in ^{100}Zr as the deformation was increased due to the addition of a neutron pair. A value of 4.8 is then obtained for the ratio $E_{0_2^+}/E_{2_1^+}$, which fits well into the systematics in this mass region.[27] The ratio increases from 3.7 to 4.6 between the isotones ^{106}Ru and ^{104}Mo, respectively.

The character of the 891-keV level is not clear. If

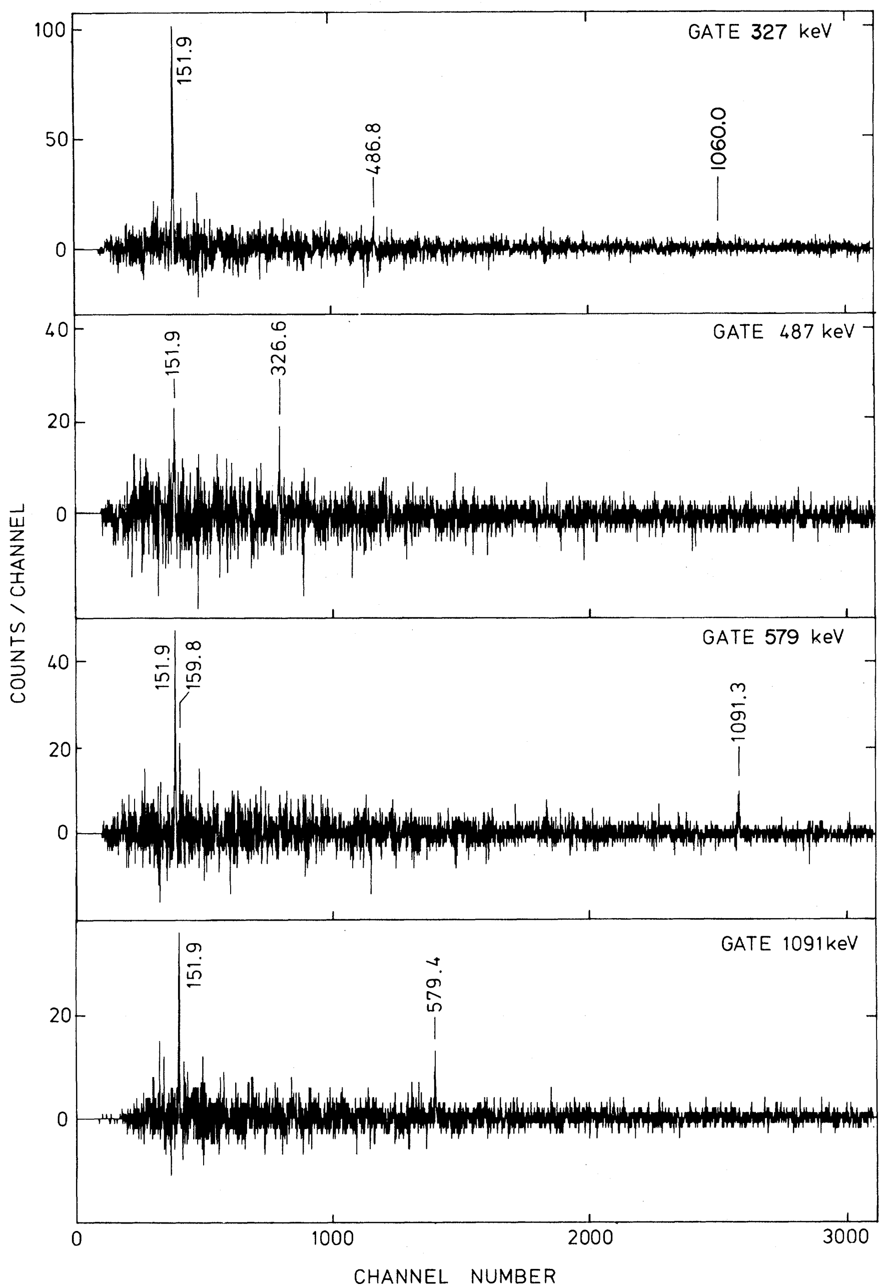

FIG. 6. Examples of the γ-γ coincidence spectra for ^{102}Zr. The spectra were measured with the 150 cm^3 Ge(Li) detector. The gates were set on the spectra of the 61 cm^3 Ge(Li) detector.

it corresponds to the 2_2^+ level seen in ^{100}Zr at 878 keV, one would expect to observe decay to the 2_1^+ state at 152 keV. The upper limit for such a transition amounts to one tenth of the intensity of the 579-keV line, as can be deduced from the coincidences with the 152-keV γ ray. Also, no ground state transition from the 891-keV level has been observed, but it is not possible to place a very restrictive upper limit on its intensity due to the weakness of ^{102}Y in the singles spectrum.

The experimental findings can be understood if the level at 891 keV is the 2^+ state based on the 0_2^+ band head (the 2^+ level of the β band). Then the 160-keV depopulating transition is the 2_β^+ to 0_β^+ in-

TABLE II. $\gamma\gamma$ coincidences observed in ^{102}Y decay.

Gating transition (keV)	Definitely coincident γ rays (keV)	Possibly coincident γ rays (keV)
15.7 (Zr $K\alpha_1$)		152
152	15.7, 327, 579, 1060, 1091	487
160	152, 579	
327	152, 487	15.7, 1060
487	152, 327	
579	152, 160, 1091	
1060	152	327
1091	152, 579	

terband transition, which can be fairly strong. This interpretation is supported by the fact that the energy difference of 160 keV between the 891- and 731-keV levels is similar to the energy difference of the 2_1^+ and 0_1^+ states.

The alternative interpretation of the 731-keV level as the 2_2^+ state is not in agreement with the experimental facts since no transition into the ground state has been observed. Coincidences with the 1091-keV γ ray (Fig. 6) show that the 731-keV ground state

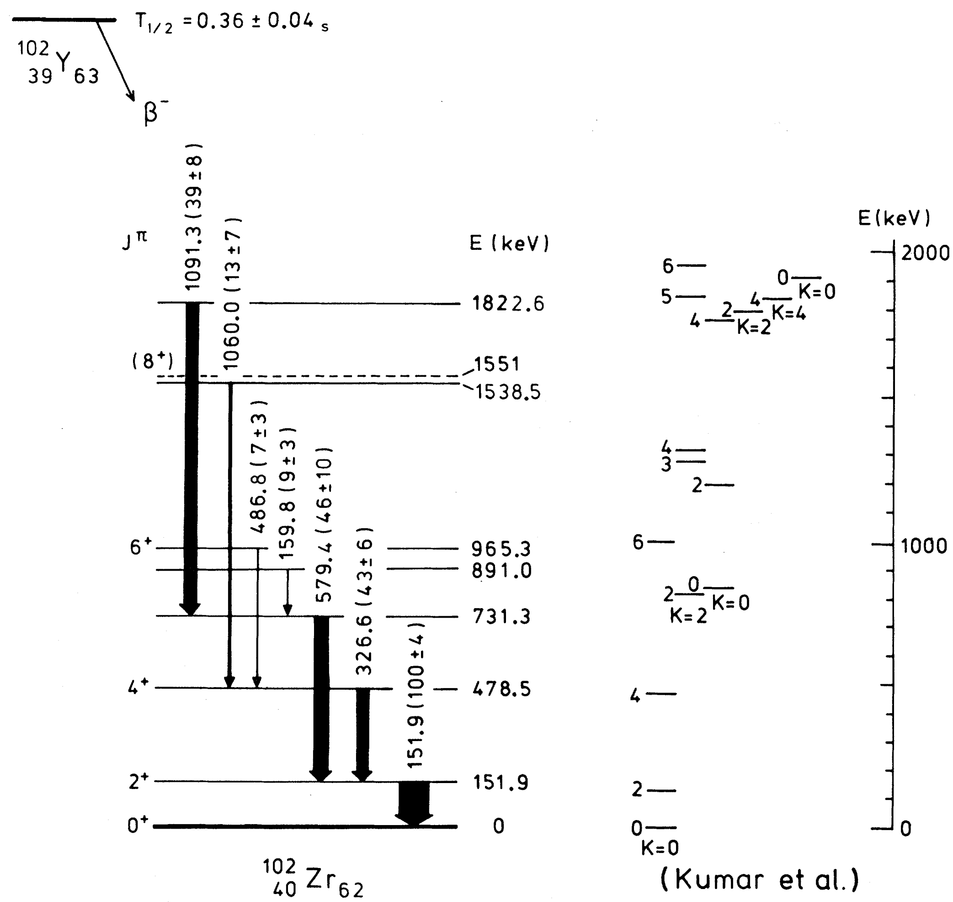

FIG. 7. Proposed level scheme for ^{102}Zr. Part of the results of the calculations by Kumar et al. (Ref. 14) are also shown. The value for Q_β is taken from Ref. 24.

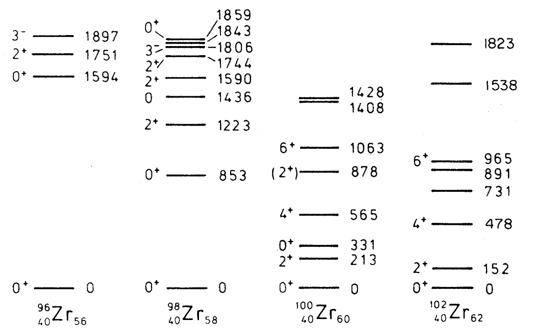

FIG. 8. Systematics of the low-lying levels in the neutron-rich even-mass Zr isotopes.

transition must have an upper limit for its intensity of approximately one fourth that of the 579-keV transition. This would mean that

$$R=\frac{B(E2{:}2_2^+\to 2_1^+)}{B(E2{:}2_2^+\to 0_1^+)}>15\ ,$$

which is by far larger than the rigid rotor value of 1.4. It is also larger than the known values around $A=100$. The values of $R=11.1$ and 3.2 have been determined for the isotones ^{106}Ru and ^{104}Mo, respectively.[28,29] The decrease of R between these isotones is considered to be a result of the strengthening of the deformation. This trend should continue towards ^{102}Zr, which is more strongly deformed than ^{104}Mo.

If the 731-keV level has $J^\pi=0_1^+$, then an isomeric state must exist in ^{102}Y, since the 731-keV level is fed almost exclusively through the 160- and 1091-keV transitions. The 891- and 1823-keV levels must thus have low spin and are not expected to be populated by the same β decaying isomer as the 6_1^+ and 4_1^+ levels.

We present here a first attempt to look at the level structure of ^{102}Zr in detail. Due to the short half-life and low fission yield, only a portion of the low-lying level structure has been elucidated; thus our analysis given above is quite speculative. Additional experiments with better statistics will be required to clarify the structure. The fact that the decay of ^{102}Y can at present only be studied in beam at JOSEF renders angular correlation studies for the identification of level spins extremely difficult, since the beam has a diameter of 10 cm. Only the study of conversion electrons might provide further information.

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