Systematic features in the structure of doubly odd nuclei around $A \approx 80$ mass region: Band structure in ^{76}Rb

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Multiple-particle γ-ray coincidence techniques have been used to establish the high spin structure of ^{76}Rb. Two $\Delta I = 1$ bands were found built on the $I^\pi = 1^-$ ground state and on the $I^\pi = (4^+)$ isomeric state at 316.8 keV energy. Systematic of positive parity bands seen in the Br-Kr-Rb isotones with $N = 39$ and 41 is discussed.

The systematic study of the doubly-odd nuclei in the $A = 70-80$ mass regions has proved to be both interesting and challenging. The main characteristic for nuclei near the middle of the $28 \leq (N,Z) \leq 50$ region is the onset of a very large deformation[1] of $\beta = 0.4$ and the difficulty to define a nuclear shape for the doubly-even nuclei near the ground state. This characteristic is described introducing the concept of soft nuclei that expresses the coexistence of spherical and prolate shapes, the change of the moment of inertia with angular momentum, and the rapid change of some nuclear properties with particle number.[2]

The microscopic structure of the nuclei is primarily determined by the $p_{1/2}$, $f_{5/2}$, $p_{3/2}$, and the intruder $g_{9/2}$ orbitals which is the origin of the positive parity excited band seen in odd and doubly odd nuclei.

Considering the doubly odd nuclei ^{78}Rb and ^{76}Br in which the odd particles occupy the $g_{9/2}$ shell, the resulting positive parity band shows a remarkable resemblance[3] to the $5/2^+$ band measured in the odd neutron ^{77}Kr nuclei. An almost equal energy, for the first three excited states, as well as similar level staggering for the $N = 41$ ^{76}Br-^{77}Kr-^{78}Rb isotones was measured. These patterns have been successfully explained, for ^{76}Br and ^{77}Kr nucleus within the framework of two noninteracting particles coupled to a rigid rotor model.[4] The systematic investigation of this phenomenon continues towards increasingly neutron deficient nuclei which have larger deformation. The odd-odd nuclei probably have even larger deformation promoted by the polarizing effect of both odd particles acting on a soft nuclei. These studies present serious experimental problems as the frontiers of known nuclei are reached. However, compound nuclear reactions, using heavy ions, are the best means of producing nuclei in this region.

In this work the level scheme for the ^{76}Rb nuclei is reported. This result and the ^{75}Kr (Ref. 5) and ^{74}Br (Ref. 6) data constitute a similar Rb-Kr-Br isotone chain with a different neutron number of $N = 39$.

The decay of high spin states of ^{76}Rb was determined using the ^{40}Ca(^{39}K,γ2pn) reaction induced by the ^{39}K beam from the Brookhaven National Laboratory Tandem Accelerator at 120 MeV energy. The γ-ray spectra and coincidence data were obtained with two Ge(Li) detectors, with one of them surrounded by an anti-Compton shield, at 90° with respect to the beam axis. The isotopic identification was obtained first by analyzing the γ-γ coincidence experiment, where several unknown γ-ray cascades were found. Then the coincidence between the strongest γ rays of such cascade and the particles (p,d,α,n) emitted from the compound nucleus were analyzed. Details of the experimental setup and measurements are reported in Ref. 5.

The gamma-proton-neutron coincidence spectra are dominated by intense reaction channels such as 2pn and 3pn leading to levels of ^{76}Rb and ^{75}Kr, respectively. An excitation function experiment performed at 110, 120, 125, 130, and 140 MeV in coincidence with neutron, determined that γ rays assigned to ^{75}Kr increase their intensity with the beam energy. On the other hand, γ-ray cascades, which were identified with the transition energy between the lowest states such as 101.2 keV, 180.2 keV, and 104.4 keV, show a broad maximum at 120–125 MeV, suggesting a lower number of emitted particles than in the case of the 3pn reaction channel. The relative cross sections for the ^{76}Rb nuclei, determined by measuring the decay to ^{76}Kr levels, show a similar behavior as a function of the beam energy. The rate of population of ^{76}Rb nuclei relative to ^{76}Kr is as much as 25%. This result allows to exclude the possibility of interpreting the observed γ-ray intensities as being produced by reactions with contaminants or to the use of natural target materials.

The investigation determined three γ-ray cascades and an intense γ ray of 70.5 keV energy that populated levels of the 101.2 keV cascade. The absence of other γ rays in coincidence with these low energy transition suggest the existence of an isomeric state at 316.8 keV with a half-life longer than 50 ns. The angular distribution coefficients as well as the γ-ray intensities are reported in Table I. Moltz *et al.*[7] from decay and magnetic moment measurements[8] strongly suggested an $I^\pi = 1^-$ for the ground state of ^{76}Rb. To determine the energy of the different band heads a study of the γ-ray intensity balance from in-beam and off-beam measurement was performed. A single spectrum was collected during 2 min of irradiation, and immediately after the irradiation stopped, singles were accumulated for a period of approximately 8 min to study the half-life of the γ rays.

The relative cross sections for the ^{76}Rb nuclei were determined measuring the intensity decaying to the 424.0 keV level of the ^{76}Kr nuclei. A value of $\sigma(^{76}\mathrm{Rb})=100(20)$ was obtained. The corresponding relative cross sections for the different cascades were the following: $\sigma(101.2)=100(5)$, $\sigma(180.2)=54(3)$, and $\sigma(104.4)=26(3)$. These results showed that the most intense cascade, namely, the 101.2 keV, exhausted all the intensity available for ^{76}Rb nuclei. Assuming that the cascade populates the ground state, the intensity balance therefore suggested that the 180.2 keV populates the isomeric state. The low intensity for the 104.4 keV cascade made it difficult to determine its position unambiguously. The isomeric state at 316.8 keV energy is deexcited by a 70.5 keV transition to the 246.3 keV level. From the intensity balance of the 246.3 keV level an upper limit for the total conversion coefficient of $\alpha(70.8)=1.1(2)$ was determined. Assuming that only the 180.2 keV cascade populates the 316.8 keV level, a lower limit of $\alpha(70.5)=0.4(2)$ was obtained. Considering that the total conversion coefficient for pure quadrupole and dipole transitions is more than 6 and around 0.3–0.4, respectively, we suggested that the 70.5 keV γ ray is of dipole character. The parity of the band built at the isomeric state has been suggested to be positive from systematic arguments. A recent work of Hofmann *et al.* (Ref. 13) used the velocity separation technique to search for short isomeric states populated in this mass region. They found four γ rays with energies of 70.55, 145.09, 101.3, and 246.3 keV which decay with a half-life of 3.2 μs and were assigned to the decay of ^{76}Rb nuclei. Although γ-γ coincidences and angular distributions were not measured, the proposed decay scheme including an isomeric level at 316.9 keV is in agreement with the one proposed in the present work.

The proposed decay of ^{76}Rb is shown in Fig. 1. The cascade feeding the isomeric state collects most of the in-

TABLE I. Energies, intensities, and angular distribution coefficients of γ rays assigned to the ^{40}Ca(^{39}K,2pn)^{76}Rb reaction at 120 MeV energy.

$E_\gamma(\pm 0.3)$ (keV)	I_γ[a]	A_2	A_4
70.5	41		
101.2	100	−0.15(4)	−0.08(4)
104.4	18	0.3(2)	−0.1(1)
145.0	100	−0.21(3)	0.02(4)
180.2	54	−0.6(2)	0.01(6)
208.2	15	−0.34(8)	−0.03(4)
210.0	31	−0.7(2)	0.04(8)
235.1	9	−0.2(1)	−0.1(2)
241.5	26	−0.5(2)	0.03(5)
246.3	6		
270.7	15		
278.7	10	−0.7(3)	0.1(4)
290.8	14	−0.7(3)	0.1(4)
320.4	3		
323.2	2		
333.2	7	−0.8(4)	0.01(4)
352.9	2		
363.8	3	−0.4(3)	0.05(8)
390.3	4		
392.2	2		
443.3	3	0.2(3)	−0.4(6)
480.6	3		
549.2	5	0.2(1)	−0.2(3)
555.2	2		
623.6	2		
642.2	2		
643.2	1		
725.6	1		
762.7	1		

[a]The intensities, at 90° with respect to the beam direction, are normalized to that of the 101.2 keV transition. The errors are 10% for the strongest peaks and 40% for the weakest ones. Most of the intensities are estimated from the coincidence results.

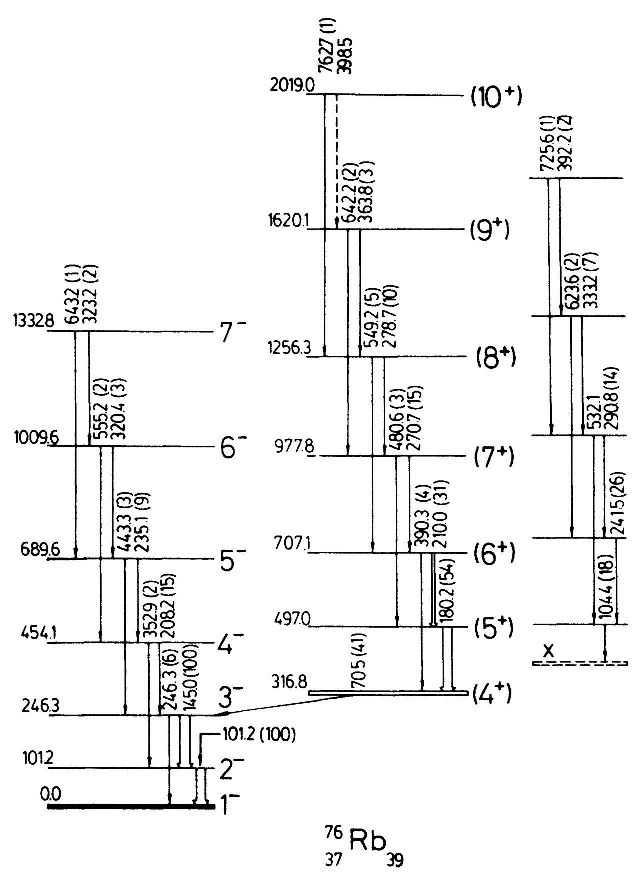

FIG. 1. Three independent groups of γ rays, which show a very regular increase in transition energy with angular momentum, suggesting strong collective effects, are proposed. The energy for the band head labeled by an $\times$ indicates that its position is uncertain.

tensity, and through the 70.5 keV γ ray, strongly populates the two low energy states of the 1^- ground state band. The three cascades of γ rays, found in the present work, show a very regular increase in their transition energies with increasing angular momentum; a pattern which is suggestive of collective structure.

If we observe in detail the suggested positive parity excitation of ^{76}Rb and compare it with the positive parity band of ^{75}Kr and ^{74}Br $N=39$ isotones, a very interesting parallelism emerges. Figure 2 shows the systematic for the positive parity state for Rb-Kr-Br isotones nuclei with $N=41$ and $N=39$. The previously noted[3] parallelism for the ^{78}Rb-^{77}Kr-^{76}Br ($N=41$) isotones may be now extended to the ^{76}Rb-^{75}Kr-^{74}Br ($N=39$) isotones.

Figure 2 shows that the energy of the lowest three states is almost the same for each isotone chain suggesting that the effect of the odd proton is not very important. On the other hand, the increase in level spacing for the states $5/2^+$-$7/2^+$-$9/2^+$ of the ^{77}Kr to ^{75}Kr odd-neutron nuclei is followed closely by the energy spacing of the corresponding doubly-odd isotones indicating the relevant role of the odd neutron particle. A possible description could be attempted taking into account that the positive parity state can be described coupling two odd particles in the high-J intruder $g_{9/2}$ shell where the Fermi levels for a proton ($Z=37$) are near $\frac{1}{2}[440]$ and $\frac{3}{2}[431]$ and for a neutron ($N=39$) at $\frac{5}{2}[422]$ Nilsson orbitals. Therefore odd proton excitations present a decoupled band structure as shown in Fig. 2 for Br ($Z=35$) and Rb ($Z=37$), which show almost constant energy.

The positive parity $5/2^+$ bands in ^{77}Kr to ^{75}Kr isotopes show an increase in level spacing as well as a decrease in level staggering which suggests, as discussed in Ref. 5, an increase in deformation. These effects are also clearly shown in the doubly odd systems comparing the positive parity band going from ^{78}Rb to ^{76}Rb (Figs. 2 and 3), in which the decrease in level staggering is apparent. Figure 3 shows the moment of inertia as a function of the angular momentum I for the suggested positive parity bands. As it can be seen, the Coriolis perturbation shows an abrupt decrease in ^{76}Rb for the $I^\pi=(4^+)$ and $I^\pi=1^-$ bands displaying an almost constant moment of inertia.

It is a well-known fact for nuclei near the $A=70-80$ mass region that odd particles can strongly polarize the soft core nuclei, changing the deformation, as it can be seen when comparing ^{73}Br (Ref. 9), which has a deformation of $\beta=0.4$ with the core ^{72}Se of $\beta=0.3$. The odd-even neighboring nuclei of ^{76}Rb showed a strong deformation of $\beta=0.4$ for ^{77}Br (Ref. 10) and $\beta=0.35$ for ^{75}Kr.[5] The doubly-even ^{74}Kr nuclei,[11] suggested as the core of ^{76}Rb nuclei, showed that the moment of inertia increases from 10 MeV^{-1} to 33 MeV^{-1} going from $I=2$ to $I=10$. In contrast, the moments of inertia for the $I^\pi=(4^+)$ and 1^- bands in ^{76}Rb are 55 MeV^{-1} and 40 MeV^{-1}, respectively, and are almost independent of angular momentum, suggesting that the odd particles polarize the soft core in such a way to stabilize a large prolate deformation.

A very important effect shown in Fig. 3 is the abrupt

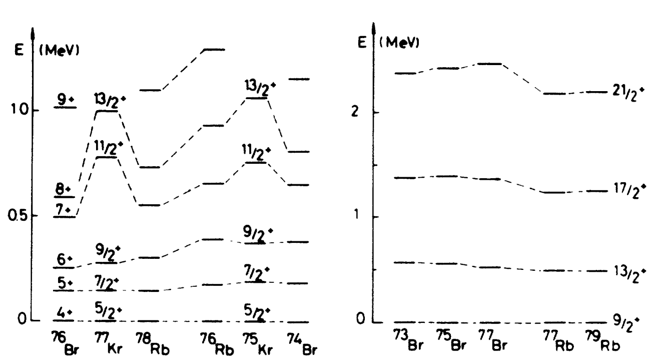

FIG. 2. The suggested positive parity band found in ^{76}Rb is compared to that in ^{74}Br and to the $5/2^+$ band of ^{75}Kr. The similarities in excitation energy as well as in the level staggering found previously for the $N=41$ isotone is extended to the ^{76}Rb-^{75}Kr-^{74}Br ($N=39$) isotones. The positive parity excitation for the neighboring odd proton nuclei $Z=35$ and 37 shows a very regular behavior almost independent of the number of particles.

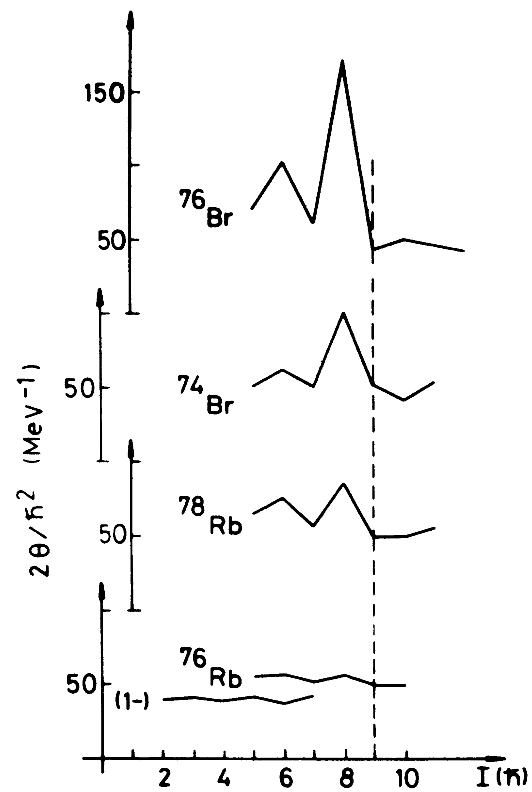

FIG. 3. The evolution of the moment of inertia with spin for the suggested positive and negative parity band of ^{76}Rb compared with the positive parity bands of neighboring doubly-odd nuclei. The almost constant moment of inertia for both bands in ^{76}Rb and also the abrupt change of the levels staggering from $I=9$ onwards are apparent.

attenuation of the level staggering from $I = 9$ onwards. These results are correlated with the maximum angular momentum obtained with both particles totally aligned in the $g_{9/2}$ shell and also to some band crossing phenomena that Wells *et al.*[12] have pointed out for the ^{76}Br decay study. Future experimental work, such as electron conversion study to establish the parity of these bands and half-life measurements to investigate the evolution of the nuclear shape towards high spin, is called for.

Finally, the rather simple systematic features that emerge from the study of doubly odd nuclei near $A \approx 80$, and in particular the ^{76}Rb nuclei, which may have the largest deformation near the ground state, create a challenge to future theoretical and experimental work.

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