THE EXCITED STATES OF ^{79}Kr OBSERVED IN THE DECAY OF ^{79}Rb

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The level scheme of ^{79}Kr was investigated from the decay of 23.8 min ^{79}Rb. Using Ge(Li) detectors and scintillator NaJ(Tl) counters single, prompt coincidence and delayed coincidence spectra were measured. For the 146.8 keV state the value of the life time of (79.1 ± 1.5) nsec was obtained, which is in good agreement with previous results, and for the 182.3 keV state the upper limit of 0.6 nsec was estimated. From the end-point energies of positron spectra in coincidence with prominent γ-rays the decay energy of (3726 ± 60) keV of ^{79}Rb was determined. The proposed level scheme of ^{79}Kr incorporates all the observed transitions except four weak ones. The log *ft* values (or their limits) were determined for β transitions to the excited states of ^{79}Kr.

The results of this work are compared with those of Lingemann *et al.* and differences in the spin assignments of some excited states of ^{79}Kr and of the ground state of ^{79}Rb are discussed. A comparison of the low-lying states of ^{79}Kr and ^{77}Se is made and a desciiption of some excited states in the framework of the Nilsson model is also discussed.

1. *Introduction*

The existence of a strong deformation of nuclei in the region $28 \leqslant Z, N \leqslant 50$ is suggested by several authors [1–4] and it seems that some experimental facts, such as large quadrupole moments, considerable deviations of the magnetic moments from the Schmidt

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lines, and other properties of the low-lying states for many of these nuclei, confirm this hypothesis. One cannot however establish decisively whether the Nilsson model gives a good description of the properties of nuclei in this region, as experimental data collected up to now are rather scarce.

Engels in his work on ^{77}Se [1] has tried to explain the observed properties of this nucleus in a consistent way in terms of the strong coupling model, and claims that the description is satisfactorily comparable with the one obtained for nuclei in the rare earth region. The ^{79}Kr nucleus differs from the ^{77}Se by an addition of a pair of protons and one may expect quite similar properties for these two nuclei. It seemed worthwhile to investigate excited states of ^{79}Kr fed in the ^{79}Rb decay and to look for analogies with ^{77}Se.

The decay of the 24 min ground state of ^{79}Rb was studied by several authors [5–10]. In 1956 Chaminade *et al.* [6] observed for the first time the ^{79}Rb activity and in 1968 the measurements of Toeset and Aten [9] provided a list of energies and intensities of 19 gamma transitions identified in the ^{79}Rb decay.

The isomeric state at 130 keV in ^{79}Kr, with the half-life of (55 ± 2) sec was discovered in 1940 by Kreutz *et al.* [5]. The ISOLDE group in CERN confirmed its existence [10] and redetermined the half life as (50 ± 3) sec. This group established the E3 character of the 130 keV transition from the isomeric state to the ground state from the measurement of the $K/(L+M)$ ratio. For the second excited state in ^{79}Kr, measurements of Bleck *et al.* [8] provided the values of its half-life of (77.7 ± 1.5) nsec and of the g-factor $g = (0.448 \pm 0.004)$.

A note about the preliminary results of the present work is contained in [11], and in the course of the elaboration of the whole material, Lingemann *et al.* published their work [12] on the detailed study of the ^{79}Rb decay.

The energies of the gamma transitions and the decay scheme established in the present investigations are in good agreement with the results of Lingemann *et al.* However, in the low energy part of the gamma spectrum there exist quite large and systematic differences in transition intensities (see Table I). These differences cause changes in $\log ft$ values of β^+ transitions to particular states and consequently some spin assignments are also changed.

Moreover, some additional gamma transitions in the high-energy part of the gamma spectrum were identified and the level scheme of ^{79}Kr was enlarged. The life-time of the 146.8 keV excited state was remeasured. Due to its fairly large value, delayed — coincidence measurements provided valuable information for the establishment of the decay scheme.

Furthermore, on the basis of analogies with the ^{77}Se nucleus and following Engels [1], the authors try to interpret some of the observed states of the ^{79}Kr nucleus.

2. *Experimental procedure*

1. Sources

The ^{79}Rb sources were obtained in the ^{71}Ga (^{12}C, $4n$) reaction, bombarding a thin target of Ga_2O_3, enriched in ^{71}Ga isotope, by 65 MeV ^{12}C ions from the U-300 heavy-ion cyclotron of the Laboratory of Nuclear Reactions of the JINR in Dubna.

The careful measurements of the excitation functions for the ^{71}Ga (^{12}C, xn) reactions were carried out, since similar irradiations were applied for investigations of the ^{78}Rb decay and the search for the metastable state in ^{80}Rb [17]. In these measurements the 1 mg/cm^2 Ga_2O_3 target, placed on a thin 1.3 mg/cm^2 Al foil, was irradiated during 5-minute periods with ^{12}C ions of energies ranging from 45 to 80 MeV. The recoiled nuclei were collected on a thin Al foil set about 0.3 cm behind the target. This Al foil with Cs carrier

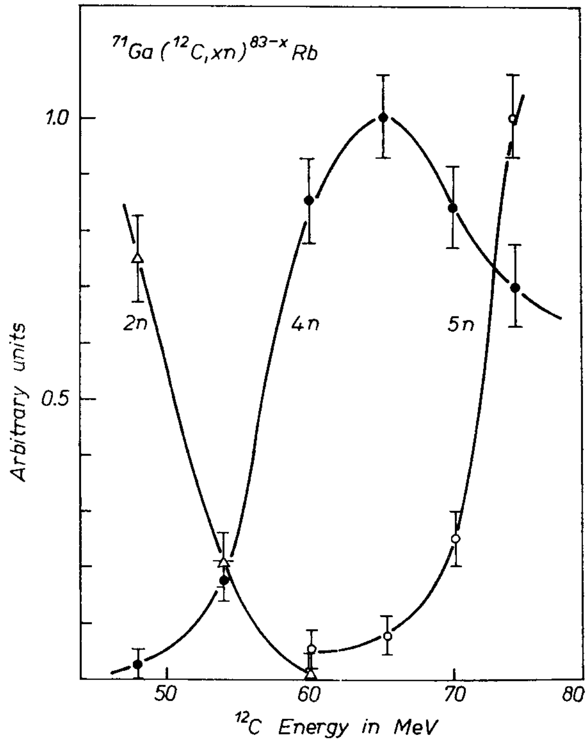

Fig. 1. Excitation functions for the reaction ^{71}Ga(^{12}C, xn)$^{83-x}$Rb, with two — (Δ), four — (●) and five (○) evaporated neutrons. The excitation function for the reaction ^{71}Ga(^{12}C, 3n)^{80}Rb was not determined since ^{80}Rb could not be observed in off-line experiments

added was then dissolved in HCL and after adding sodium tetraphenylboran rubidium was extracted. Experiments checking the efficiency of the rapid (less than 5 minutes) chemical processes showed fluctuations in efficiency ranging from 85 to 100 %. The normalization to the ^{12}C beam intensity was performed by current measurement during irradiations as well as by the activation method.

The observed changes of the intensities of definite gamma transitions in sources from successive irradiations furnished the energy dependence of the cross-sections for ^{71}Ga (^{12}C, xn) reactions. These dependences are shown in Fig. 1.

On the basis of these results, the energy of 65 MeV for ^{12}C ions was chosen for obtaining the ^{79}Rb sources, as the cross-section for ^{71}Ga (^{12}C, 4n) reactions reaches its maximum at this energy.

The sources were obtained in 10–15 min. irradiations and the measurements began immediately after chemical purification. The impurities in such sources never exceeded 1%, though in some coincidence experiments chemically non-purified sources were used and the impurities were considerably higher.

2. Apparatus

For single spectra measurements of the gamma radiation two Ge(Li) detectors were used: a Ge(Li) detector of 13 cm^3 volume of resolution 3.6 keV for the 662 keV line and a Ge(Li) detector of 33 cm^3 volume, of resolution 4 keV for the 1330 keV line.

Gamma-gamma coincidence spectra were measured with the aid of a 10 cm^3 Ge(Li) detector of resolution of about 6 keV and the 13 cm^3 Ge(Li) detector.

For $\beta^+ - \gamma$ coincidence spectra a plastic scintillator NE102 of 4 cm × 2.5 cm and the 13 cm^3 Ge(Li) detector were used. The energy resolution of the plastic scintillator was about 17% for the 976 and 626 keV lines.

The half-life measurements for the 145.8 keV level in ^{79}Kr were performed by the delayed coincidence method, using two 2″ × 2″ and 1.5″ × 1.5″ NaJ(Tl) scintillators and RCA 6810A photomultipliers. Two thin 1″ × 1″ and 0.5″ × 1.5″ NaJ(Tl) scintillators and XP1020 photomultipliers were used for the upper limit estimation of the life-time of the 182 keV level.

Finally, delayed coincidence measurements were performed using a 2″ × 2″ NaJ(Tl) scintillator and the 13 cm^3 Ge(Li) detector.

3. Experimental results

1. Single spectra

The examples of single spectra of the gamma radiation from the ^{79}Rb decay are shown in Figs 2 and 3. The low energy part of the spectrum (Fig. 2) was measured with the 13 cm^3 Ge(Li) detector, and the high energy part (Fig. 3) with the 33 cm^3 Ge(Li) detector, using an absorber of 3 mm Pb, 1 mm Cd, and 0.5 mm Cu.

The identification of lines which belong to the investigated decay was performed by the time analysis of their decays as well as by examination of the spectra obtained in measurements of excitation function described above.

The energies and the relative intensities of the observed transitions in the decay of ^{79}Rb are summarized in Table I. These values are mean values obtained from a number of measurements made with different sources and with two different detectors for various source-detector distances, for which the energy and efficiency calibrations were performed independently. In this table the results of Lingemann *et al.* [12] are also given for comparison. The agreement in energy determination is fairly good.

The relative intensities given in Table I show deviations from the results of Lingemann *et al.*, especially in the low energy region, where discrepancies reach about 20% for the majority of strong transitions, the present values being systematically higher than

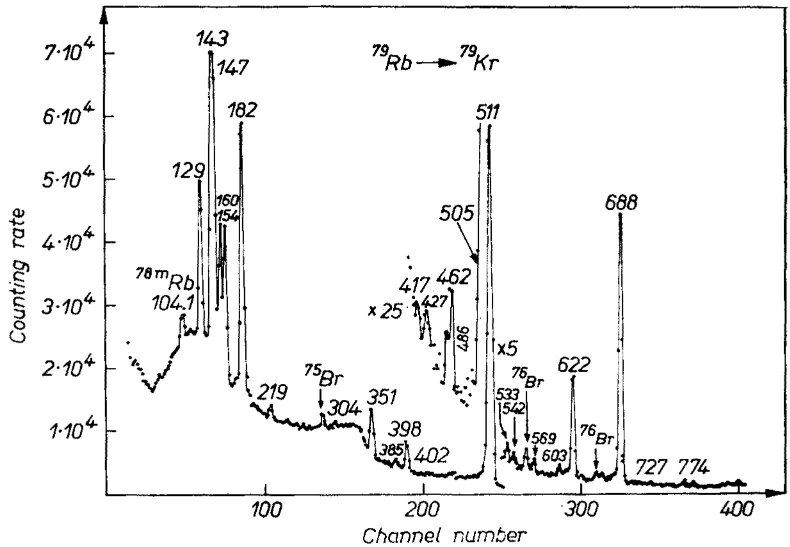

Fig. 2. The low-energy part of the gamma spectrum from the decay of ^{79}Rb taken with 13 cm^3 Ge(Li) detector

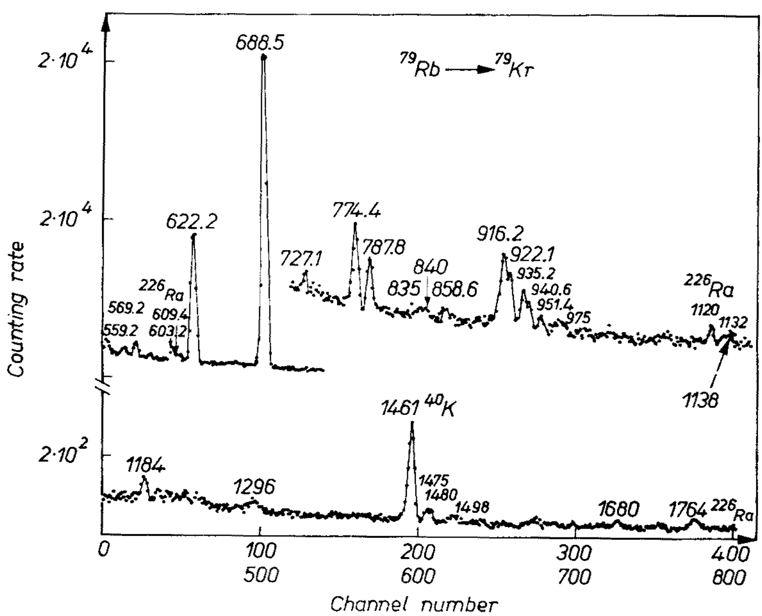

Fig. 3. The high-energy part of the gamma spectrum from the decay of ^{79}Rb taken with the 33 cm^3 Ge(Li) detector using an absorber of 1 mm Pb, 1 mm Cd, 0.5 mm Cu

TABLE I

Energies and relative intensities of γ-rays from the decay of ^{79}Rb

E (keV)		$I\gamma/I_{688}$	
This work	Ref. [12]	This work	Ref. [12]
17.2±0.5[a]	17.88	5.2[a]	6.6
	52.33		1.3
	108.91		0.6
	116.68		1.0
129.6±0.2	130.01	37.2±3.8	41.5
143.1±0.3	143.49	59.2±6.0	46.6
146.8±0.3	147.23	46.2±4.6	32.2
154.2±0.3	154.84	28.7±2.9	24.6
160.2±0.3	160.68	36.8±3.7	28.9
182.3±0.2	182.82	87.1±7.2	67.2
201.5±0.4	200.72	0.8±0.3	0.7
218.6±0.3	218.76	5.1±0.6	5.0
	243.46		0.4
	285.91		3.4
304.2±0.3	303.17	2.5±0.3	1.3
	337.34		2.7
351.0±0.3	350.66	31.9±3.0	28.1
384.0±0.3	383.89	5.3±0.6	4.9
388.3±0.4	388.82	0.9±0.3	0.8
398.4±0.3	397.65	25.1±2.2	22.3
402.1±0.4	402.15	2.3±0.4	2.2
417.1±0.3		1.0±0.3	
428.6±0.3		2.3±0.4	
461.8±0.3	461.49	5.0±0.5	4.8
	486.39		1.2
505.0±0.5	505.30	55.0±8.0	53.6
511.0	511.01	665 ±50	700
524.0±0.5	524.44	1.0±0.3	0.8
533.3±0.3	533.23	5.9±0.5	5.6
	548.70		2.8
569.0±0.3	569.05	4.0±0.4	4.7
603.2±0.3	603.19	3.0±0.3	3.0
622.1±0.2	622.08	37.0±3.2	29.4
	643.62		1.0
	654.49[c]		1.0
688.1±0.2	688.12	100	100
728.1±0.4		0.5±0.2	
774.4±0.3		2.9±0.3	
787.8±0.3	787.44	1.8±0.2	0.9
835.0±0.6[b]		0.2±0.1	
840.5±0.6		0.3±0.1	
858.6±0.5		0.4±0.1	
	884.1		0.4
916.2±0.4	915.85	3.1±0.5	2.3

Table I — continued

E (keV)		$I\gamma/I_{688}$	
This work	Ref. [12]	This work	Ref. [12]
922.1±0.4	921.70	1.8±0.4	1.5
935.2±0.5	934.69	1.3±0.2	1.2
940.6±0.5	941.32	0.7±0.2	0.7
951.4±0.6		0.4±0.1	
975.0±0.8[b]		0.2±0.1	
	1016.77[c]		0.6
1132.5±0.8[b]		0.3±0.1	
1138.9±0.8		0.3±0.1	
1184.1±0.5	1184.3	1.0±0.2	0.9
	1194.8		0.9
1296 ±1		0.3±0.1	
1475 ±1		0.5±0.2	
1480 ±1		0.4±0.2	
1498 ±1		0.3±0.2	
	1517.1		0.2
1680.1±1		0.7±0.2	
	1743.2		0.3
2060 ± 1		0.3±0.1	
2173±1		0.3±0.2	

[a] unobserved transition with deduced energy and intensity (see text),
[b] transitions not placed in the decay scheme,
[c] sum — peaks.

in Ref. [12]. The reason for such a divergence might be a systematic error caused by the efficiency calibration of the detectors, though one can also observe a discrepancy of about 25% in the relative intensity of the 622 keV line, which is situated near to the 688 keV line used for normalization. From the single gamma spectrum shown in Fig. 1 in Ref. [12] it is seen that the effects of summing in the crystal were quite large. The 654 and 1016 keV lines seen in this spectrum and given in the table of the gamma transitions are due to these effects. It is possible that the contributions of the sums (182+511 and 182+505) increase the intensity of the 688 keV line, causing the observed divergence.

The relative intensities of the 511 keV annihilation quanta and of 129.6 keV ground state transition from the 55 sec isomeric state, were determined in a detailed time analysis.

As a byproduct of this experiment the half-life of the ^{79}Rb decay was determined $T_{1/2}$ = (22.8±0.5) min. in agreement with the previous results [6, 7, 9, 12].

The higher statistics in the high-energy part of the spectrum permitted us to identify new lines and to eliminate some given in Ref. [12] which decayed with different half-lives. On the other hand, the possibility to observe some low energy transitions, which Lingemann *et al.* observed with a thin Ge(Li) detector with a beryllium window, was limited by the Ge(Li) detectors used in the present work.

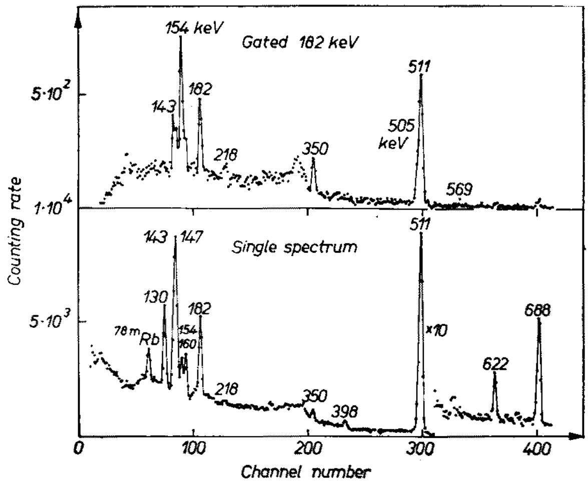

Fig. 4. The coincidence spectrum with the 182 keV gamma transition. The single spectrum given for reference

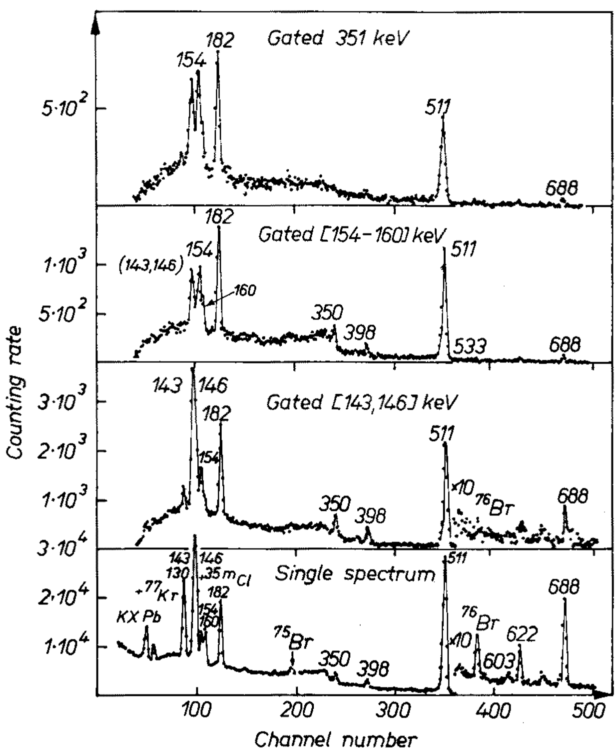

Fig. 5. The gamma coincidence spectra taken with two Ge(Li) detectors. The single spectrum is given for reference. The gated energies are indicated at the respective spectra

2. Coincidence spectra

The results of the gamma-gamma coincidence experiments performed with two Ge(Li) detectors are presented in Table 2 and examples of coincidence spectra are shown in Figs 4 and 5. From the delayed coincidence experiment the 146.8 keV transition was unambiguously fixed as depopulating the long-lived level (78 nsec) (see Fig. 6). Then, selecting from the NaJ/Tl spectrum the 146.8 keV transition and introducing a delay of about 100 nsec in the Ge(Li) detector branch, all the strong transitions which fed the long-

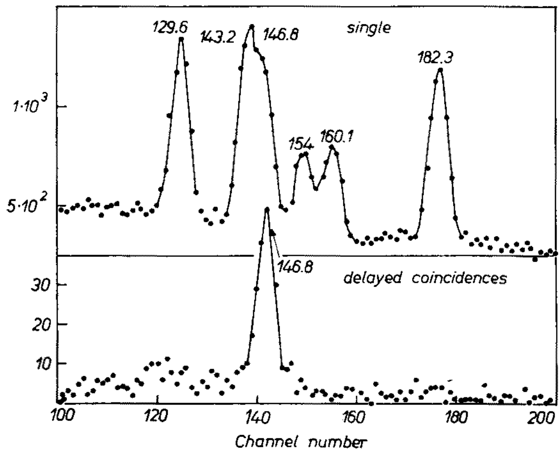

Fig 6. The spectrum of the delayed coincidences with 511 keV gate. The delay of 150 nsec was introduced to the NaJ(Tl) branch form which the gate pulse were selected. The part of the Ge(Li) single spectrum is given for reference

TABLE II

Summary of coincidence results

Transition \ Gate	143.1	146.8	154.2	160.2	182.3	351.0	398.4	622.1	688.1
143.1		+					+		
146.8	+						+		
154.2					+	+			
160.2							+		
182.3			+			+			
218.6					+				
351.0			+		+				
398.4	+	+		+					
461.8	+	+							
505.0					+				
511.0	+	+	+	+	+			+	+
533.3			+						
541.9		+							
569.0					+				
774.3		+							

lived level were observed in the coincidence spectrum. Results of this experiment are also included in Table II, and the corresponding spectrum is shown in Fig. 7. On the basis of coincidence experiments the essential frame of the decay scheme was established and it was subsequently enlarged by the analysis of the energy sum balances.

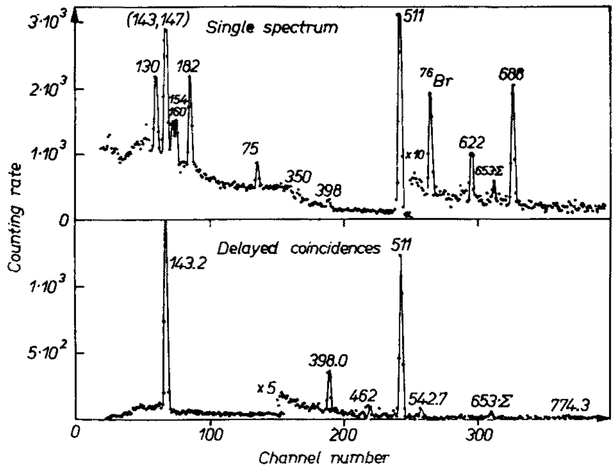

Fig. 7. Delayed coincidence spectrum with the (130–160) keV gate. The delay of 100 nsec was in the Ge(Li) branch, from which the spectrum was displayed. The sign Σ at 653 keV in both the coincidence spectrum, and the single one given for reference, indicates the sum peak

3. Positron spectra

To determine the total energy of the decay $^{79}Rb \rightarrow {}^{79}Kr$, the $\beta^+ - \gamma$ coincidence measurements were performed. For this purpose the 622 and 688 keV transitions were selected from the Ge(Li) detector spectrum and the respective coincidence spectra of positrons being detected in the NE102 plastic scintillator were observed. From these spectra Fermi — Kurie plots were drawn and the end-point energies $E^0_{622} = (2010 \pm 90)$ keV, $E^0_{688} = (1970 \pm 80)$ keV of β^+ determined.

In this experiment the energy was calibrated with the conversion lines of ^{137}Cs and ^{207}Bi and also with the β^- spectrum of ^{144}Ce with $E_{max} = 2996$ keV.

The Fermi-Kurie plots for the observed coincidence spectra of positrons from ^{79}Rb as well as for the calibration spectrum of electrons from ^{144}Ce, are shown in Fig. 8.

From the measured values and the adequate level energies, the total decay energy was obtained $Q_{622} = (3780 \pm 90)$ keV and $Q_{688} = (3680 \pm 80)$ keV. The weighted mean value of (3726 ± 60) keV deviates from the value of (3520 ± 45) keV given by Lingemann *et al.* [12]. The reason of the discrepancy is not known. In the present work, however, F.–K. plots were not corrected for the energy resolution of the plastic scintillator, but only slight deviations from the straight lines were seen on the calibration F.–K. plots for ^{144}Ce. The effects of summing of β^+ wi h Compton scattered annihilation quanta were taken into account in the plots for ^{79}Rb by neglecting in fits a few end-points.

In the log *ft* determination, the average value of $Q = 3590$ keV was used.

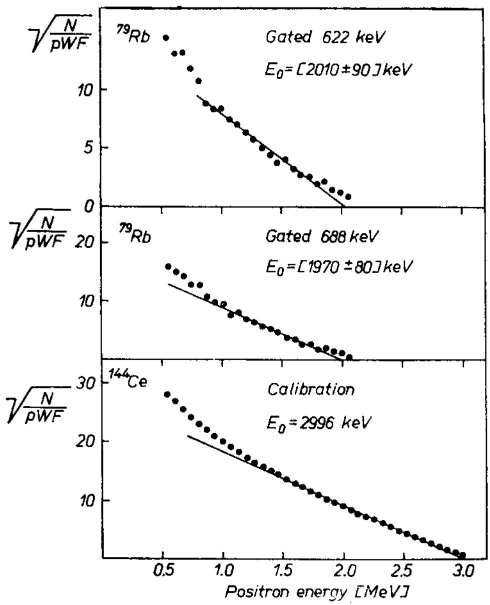

Fig. 8. The Fermi-Kurie plots for positrons from ^{79}Rb decay in coincidence with 622 and 688 keV gamma transitions, and the F.-K. plot for β^- spectrum of ^{144}Ce used for energy callibration

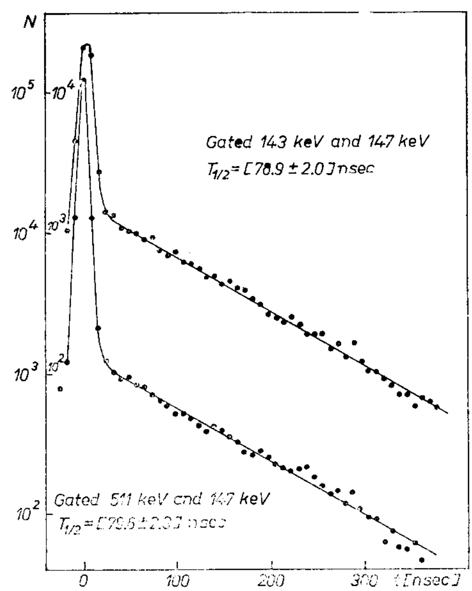

Fig. 9. The decay curves for the 146.8 keV state. In both measurements the 147 keV transition was selected from the 1.5″×1.5″ NaJ(Tl) spectrum, and 143 keV transition the upper curve and 511 keV annihilation quanta the lower curve were taken from 2″×2″ NaJ(Tl)

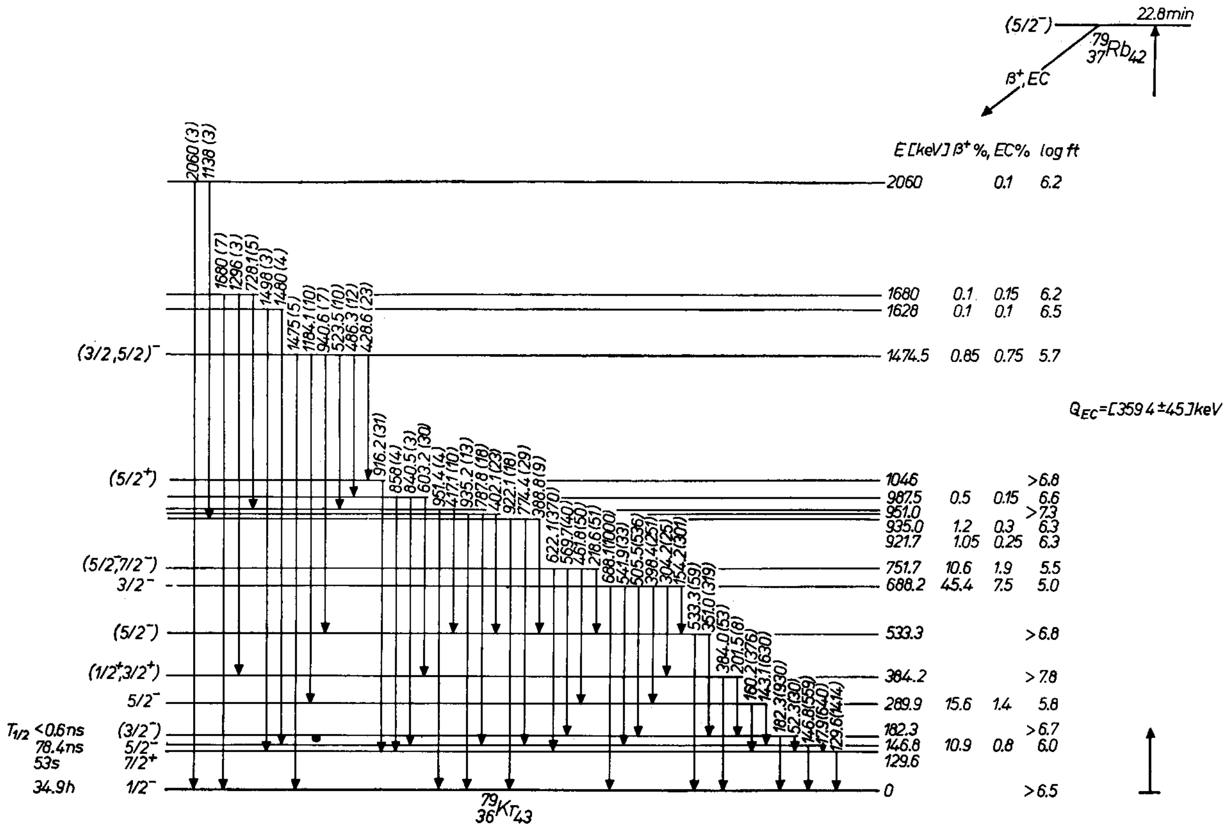

Fig. 10. The decay scheme of 22.8 min ^{79}Rb. The energies of transition are in keV. In parenthesis are the total relative intensities normalized to the intensity of the 688 keV transition

4. Life-time measurements

The delayed coincidence technique was used in the life-time measurements. The life--time of the 146.8 keV level was measured selecting from the NaJ(Tl) 1.5″ × 1.5″ scintillator counter spectrum the composite peak of (143 and 147 keV) and from the 2″ × 1.5″ NaJ(Tl) spectrum the peak of 511 keV in one measurements and the composite peak of (143+ +147) keV in the other.

The corresponding decay curves are shown in Fig. 9. From the least square fits the values of (79.8±2.3) nsec and of (78.9±2.0) nsec were obtained for the two measurements respectively. The average value of $T_{1/2}$ = 79.3±1.5 nsec agrees with the result of Bleck *et al.* [8] (77.7±1.5) nsec.

The measurements performed for the 182 keV level with the use of thin NaJ(Tl) scintillator crystals coupled to XP1020 photomultipliers did not show any difference from the prompt curve and the life-time of the 182 keV excited state was estimated as $T_{1/2} \leqslant 0.6$ nsec.

5. Decay scheme

The decay scheme of ^{79}Rb established in the above-described experiments is shown in Fig. 10. The 146.8, 182.3, 289.9, 533.3, 688.2, 751.7, and 921.7 keV levels were strongly confirmed by the coincidence results. The other levels were introduced on the basis of the energy sum balances. Only 4 transitions from the total number of 48 observed were not placed in the decay scheme.

From the intensity balance, accounting for the conversion of low-energy transitions, the intensity of 511 annihilation quanta, and taking for the total decay energy the value of 3590 keV and for the half-life of the ^{79}Rb decay the mean value of (22.9±0.4) min, the log *ft* values for β^+ branches were determined from Moszkowski's nomograms (Ref. [17]) (for allowed and forbidden β transitions theoretical EC/β^+ ratio were taken). These values are given in Fig. 10.

4. *Discussion*

1. Spin assignments

Before the paper [12] was published, in ^{79}Kr only the spin and parity of the ground state (1/2$^-$) and of the 129.6 keV isomeric state (7/2$^-$) were known. The spin and parity of the 146.8 keV state were not unambiguously determined by Bleck *et al.* (Ref. [8]) who left two possibilities 3/2$^+$ and 5/2$^-$. The authors of the paper [12] assign 5/2$^-$ spin and parity to this level, which is consistent with the results of the present work, in which, however, the existence of the 17.8 keV El transition was merely deduced from the necessity of depopulating the 146.8 keV level, and its intensity was calculated from the intensity balance for the 129.6 keV level, assuming that this level is not directly fed in the β^+ decay. Lingemann *et al.* observed the 17.8 keV transition and measured its intensity. Assuming its El character, they obtained for the total intensity (79±9) in comparison with the (64±9) calculated in this work (α_{tot} = 12).

The life-time of the 146.8 keV level $T_{1/2} = (78.4 \pm 1.5)$ nsec gives the enhancement factor of 3.3 for E2 ground state transition, and the hindrance factor of 2.10^4 for the El 17.8 keV transition as compared with the single particle estimates of Moszkowski.

The assignment of $5/2^-$ seems to be the most probable for the 146.8 level as spin and parity assignments other than $5/2^-$ for this state would give no consistance with the intensity of the 17.8 keV transition and the comparison of the life-time with single particle estimates would be less reliable.

The authors of Ref. [12] assign the $3/2^-$ spin and parity to the ^{79}Rb ground state on the basis of the low log *ft* values of the β^+ transitions to the 146.8 keV state and the ground state of ^{79}Kr. The intensity balance, however, based on the measurements performed in this work did not reveal β^+ branch to the ground state of ^{79}Kr, even if the higher value of the intensity of the annihilation quanta obtained in the Ref. [12] was taken into account. Though, from the experimental errors the lowest limit for the log *ft* value of the β^+ transition to the ground state of ^{79}Kr was estimated as 6.5.

For the ground state of Rb isotopes two assignments $3/2^-$ and $5/2^-$ compete and while in ^{87}Rb and ^{81}Rb the ground state is $3/2^-$ in ^{83}Rb and ^{85}Rb the $5/2^-$ takes over its role. In view of this, it is probable that the ^{79}Rb ground state has the $5/2^-$ spin and parity additionally bearing in mind the relatively high (6.5) log *ft* value of the β^+ branch to the $1/2^-$ ground state of ^{79}Kr. This assignment is assumed in further considerations.

For the 182.3 keV state Lingemann *et al.* [12] propose the $3/2^+$ spin and parity because of the observed 52 keV transition to the $7/2^+$ 129.6 keV state and because of the lack of the β^+ branch to that state.

The upper limit of the life-time of the 182.3 keV excited state $T_{1/2} \leqslant 0.6$ nsec measured in the present work brings this assignment into question. Comparing the experimental partial life-times with the single particle estimates, the 182.3 keV El transition would be retarded more than 10^4 times and the 52 keV E2 transition enhanced more than 3×10^3 times. Such an enhancement is rather doubtful and other possibilities should be analysed.

The results of this work confirm that the 182.3 keV level is not directly fed in the β^+ decay, the log *ft* lower limit being 6.7. One may consider two possibilities:

i. The observed in [12] 52 keV transition connects the 182.3 keV and 129.6 keV states. Since the possibility of $5/2^+$ or of a higher spin for the 182.3 keV state should be ruled out because of the short partial half-life of the ground state transition, only the $5/2^-$ possibility remains, bur then E2 transition would be enhanced more than 2.8×10^2 times. Such an enhancement is rather unexpected even if the 182.3 keV state has a strong collective character.

ii. The placement of the relatively weak 52 keV gamma transition in another place in the decay scheme would leave four possibilities for the spin and parity assignments for the 182.3 keV state *i. e.* 1/2 and 3/2 with positive or negative parity. Positive parity would have to be followed by retardation by more than 10^4 of the El ground state transition, and negative parity requires some special structure of the 182.3 keV state, accounting for the weakness of the β^+ branch to this state.

The above considerations do not assign unambiguously the spin and parity of the

182.3 keV state. The only purpose is to point out the possibility of $3/2^-$ assignment for this state, which will be discussed later on. The β^+ branch to the 289.9 keV state with log *ft* value of 5.8 most likely has an allowed character, though one cannot definitely exclude a non-unique first forbidden transition. Assuming, however, an allowed type of β^+ branch, from three possible values $3/2^-$, $5/2^-$, and $7/2^-$ for the spin of the 289.9 kev level, the first may be ruled out, because of the strong transition of 160 keV to the $7/2^+$ state. The fairly strong transition of 398 keV from the 688 keV $3/2^-$ level (see below) makes the assignment $7/2^-$ less probable. The remaining $5/2^-$ spin-parity assignment, proposed for the 289.9 keV level in Ref. [12] is thus confirmed in the present work.

The 384.2 keV level is not directly fed by the β^+ decay and a possible weak transition has a log *ft* value $\geqslant 7.8$. The positive parity and a low spin value 1/2 or 3/2 are probable for this state because of the transition to the $1/2^-$ ground state and the absence of 254 keV γ-ray to the $7/2^+$ level at 129.6 keV. A weak beta transition to the 533.3 keV level has log *ft* of more than 6.8, in comparison which the value of 6.3 given in Ref. [12]. It is thus difficult to say anything credible about the spin and parity of this level; but we shall return to this question later on.

The strongest branch in the ^{79}Rb β^+ decay to the 688 keV level, with log $ft = 5.0$, establishes the negative parity of this state. The strong transition to the $1/2^-$ ground state and the absence of a transition to the $7/2^+$ level at 129.6 keV permit one to assign $3/2^-$ as the most probable value of spin-parity of the 688 keV level.

For the 751.7 keV level fed by an allowed type β^+ transition, with log $ft = 5.5$, and depopulated by a strong transition to the $7/2^+$ level at 129.6 keV the possibilities of the spin-parity assignments are limited to $5/2^-$ or $7/2^-$.

The spin and parity of the 1474.5 keV level may be assigned as $3/2^-$ or $5/2^-$ due to log $ft = 5.7$ and to the fact of the existence of the ground state transition.

The 921.7, 935.0, 987.5, 1628, 1680, and 2060 keV levels have log *ft* values of 6.3, 6.3, 6.6, 6.5, 6.2, 6.2, respectively, which may prove allowed or first forbidden types of β^+ transitions to these levels. Consequently, spins may be limited to 3/2 and 5/2 for states being de-excited by crossover gamma transitions to the $1/2^-$ ground state and 5/2 and/or 7/2 for 987.5 and 1628 keV states, for which gamma transitions to the $7/2^+$ level at 129.6 keV were observed.

The 951 and 1046 levels may be only weakly fed in the β^+ decay (lower limits for log *ft* values being 7.3 and 6.8, respectively) and it is difficult to say anything decisive about their spin assignments.

2. Comparison of the excited states in ^{79}Kr and ^{77}Se

As is mentioned earlier, one may expect a similarity in the structure of the excited of the ^{79}Kr and ^{77}Se nuclei, which differ by a pair of protons.

The detailed information concerning the ^{77}Se nucleus has been compiled by Engels [1] and Sarantities and Erdal [13]. The authors of [13] concentrate on the positive parity states and compare their properties with the theoretical calculations of Ikegami and Sano [14]. Due to the negative parity of the ^{79}Rb ground state, the levels with positive parity in ^{79}Kr are very weakly fed and with the exception of the undoubtful $7/2^+$ state at 129.6 keV one cannot assign spin and parity of $5/2^+$ or $7/2^+$ to any other level.

The 1046 keV level from which only the transition of 916 keV to the $7/2^+$ state is observed and for which the log *ft* value is higher than 6.8, might be a positive parity state. However, the experimental evidence for the positive parity states is too scarce and the comparison of the level structures in ^{79}Kr and ^{77}Se is mainly concentrated on negative parity states.

In Fig. 11 the low-lying states of ^{79}Kr and ^{77}Se and the single particle level sequence obtained from the Nilsson model with spin-orbit coupling constant $\kappa = 0.05$ and with parameters $\mu = 0.35$ ($N = 3$), $\mu = 0.45$ ($N = 4$) for deformation $\delta = 0.21$ are shown.

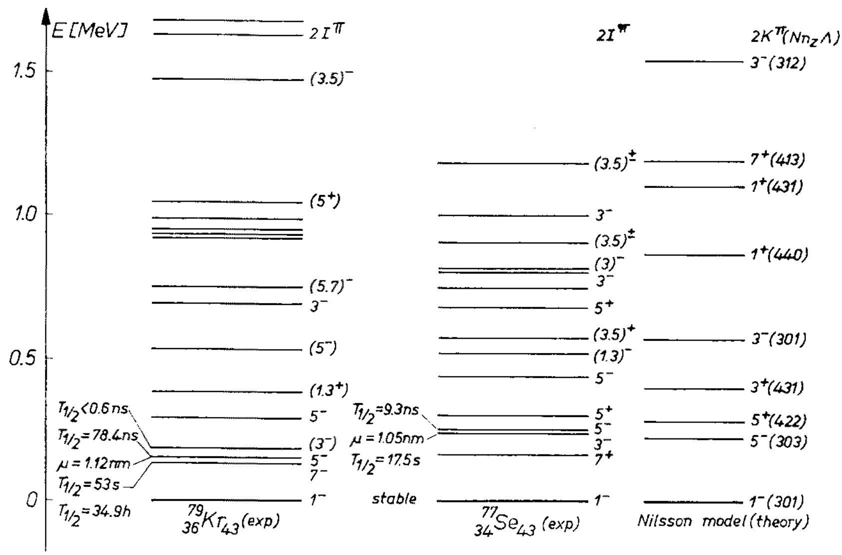

Fig. 11. Comparison of the experimental levels of ^{79}Kr and ^{79}Se (Ref. [13]) with single particle levels obtained from the Nilsson model using parameters: $\varkappa = 0.05$, $\mu = 0.35$ ($N = 3$), $\mu = 0.45$ ($N = 4$), $\delta = 0.21$. For clarity, the spin values are multiplied by the factor of 2

Heydenburgh *et al.* [15] investigating Coulomb excitation in even-even Kr isotopes, determined the $B(E2)_{0^+ \to 2^+}$ value equal to $0.51\ e^2 \cdot 10^{-48}$ cm^4 for ^{78}Kr. The deformation parameter $\delta = 0.25$ was extracted from this B(E2) assuming the rotational character of the 2^+ state in ^{78}Kr. It is of the same value as the deformation parameter for ^{77}Se [1] which was deduced from the measured B(E2) values for the $1/2 \to 5/2$ and $1/2 \to 3/2$ transitions in this nucleus.

At this deformation, the 43-*d* neutron should occupy the [301↓] Nilsson orbit, which could agree with the $1/2^-$ spin and parity of the ground states in ^{77}Se and ^{79}Kr.

The first excited state in both of these nuclei is an isomeric state $7/2^+$ at 161 keV in ^{77}Se and 129.6 keV in ^{79}Kr. Their energies are, however, much than the energy of the [413↑] Nilsson state.

The results of the (d, p) reaction studies in ^{77}Se showed that the 161 keV $7/2^+$ state has single particle properties. This would deny the interpretation of this $7/2^+$ level as an anomalous coupling state, since it should mainly include a collective component, as follows from the Ikagemi and Sano [14] calculations.

On the other hand Engels [1] pays attention to the fact that it seems to be possible to choose the parameters of the Nilsson potential in such an order as to obtain better agreement of the experimental levels in ^{77}Se with those calculated theoretically. *E.g.*, using $\kappa = 0.06$ and $\delta = 0.25$, the energy of the $7/2^+$ [413] orbital is significantly lowered, and the $3/2^+$ [431] state, which has no experimental correspondent, is simultaneously shifted upwards in energy.

The single-particle Moszkowski estimate of the life-time of the 129.6 keV level in ^{79}Kr gives the value of $T_{1/2} = 2.5$ sec. The Nilsson model gives no improvement of this estimate, the value of 1.3 sec being *ca* 40 times lower than the experimentally observed one, $T_{1/2} = (52.7 \pm 1.7)$ sec [5, 10]. A similar situation is found for the 161 keV $7/2^+$ state in ^{77}Se, where the theoretical estimate is even 60 times higher than the experimentally observed value of the life-time.

To continue, it seems that the correspondence can be observed between the 248 keV $5/2^-$ state in ^{77}Se and the 146.8 keV $5/2^-$ state in ^{79}Kr, both of them being de-excited by an El transitions to the $7/2^+$ states and by E2 transitions to the $1/2^-$ ground states. The $5/2^-$ [303] Nilsson orbit may be ascribed to them. Assuming the described above correspondence of the Nilsson orbitals and experimental levels of the ^{79}Kr and ^{77}Se, the transition between $5/2^-$[303] and $7/2^+$[413] states should be a forbidden El transition because of the change of the quantum numbers $\Delta K = 1$, $\Delta \Lambda = 0$, $\Delta n_z = \pm 1$ and $\Delta N = \pm 1$. The comparison of the partial life-times for the El and E2 transitions with the single particle Moszkowski estimates gives a hindrance factor of $2 \cdot 10^4$ for the El transition, and an enhancement factor of 3.3 for the E2 transition, as described in part 4.1 of this work. Calculations performed with the aid of Nilsson functions with $\delta = 0.25$ provide the transition probability $\lambda(\mathrm{E1}) = 3.02 \times 10^7$ sec^{-1} for the 17.8 keV transition. This gives the value of the half-life of the 146.8 keV state equal to $1.2 \cdot 10^{-8}$ sec, which is 6.5 times lower than the experimental one.

The value of the magnetic moment of the 146.8 keV state $\mu = (1.12 \pm 0.01)$ nm [9] lies below the Schmidt value for the f5/2 neutron ($\mu = 1.36$ nm). This experimental value is well reproduced in the single particle model, as well as in the Nilsson model for the $5/2^-$[303] orbit and the deformation $\delta = 0.25$, including the spin polarization effect and taking $g_s^{\mathrm{eff}} = 0.8 g_s$[1].

In the ^{77}Se nucleus the state $3/2^-$ at 239 keV and $5/2^-$ at 440 keV show strong collective properties and are interpreted as the rotational states built on the $1/2^-$[301] ground state [1].

Looking for further similarities between the level schemes of the ^{79}Kr and ^{77}Se, it seems to be quite natural to try to find such states in ^{79}Kr. One may suppose that the states observed at 182 keV and 533 keV in ^{79}Kr might hold such an interpretation. In part 4.1 of this work it was shown that it is quite possible to assign the spin and parity of these states, $3/2^-$ and $5/2^-$, respectively. The weak feeding of these levels in a direct β^+ decay in spite of the absence of the spin-parity forbidness is comparable with the feeding of the $1/2^-$ ground state, with $\log ft$ 6.5, which may be explained by the forbidness due to the change of the K quantum number, $(\Delta K) = 2$.

From the energies of the "rotational band" levels in ^{79}Kr, using the formula:

$$E_{rot} = E_0 + \hbar^2/2\theta[I(I+1) + a(-1)^{I+1/2}(I+1/2)\delta_{K,1/2}]$$

the following parameters were obtained: $\hbar^2/2\theta = 56.1$ keV, which is very near to 60.1 keV calculated by Engels for the rotational band in ^{77}Se, and the decoupling constant $a = -0.252$, which differs from the $+0.331$ calculated in Ref. [1]. The energy of the next component of the rotational band ($7/2^-$ state) calculated with these parameters is 827 keV. This level may remain unobserved in the decay of ^{79}Rb, since the direct feeding by a β^+ branch should be weak, as mentioned earlier, and it lies above the 688 and 751 keV states from which the 182 and 533 keV levels are mainly fed.

To the state $3/2^-$ at 688 keV one may assign the $3/2^-$[301] Nilsson orbit, similary as to the state at 520 keV in ^{77}Se [1].

In the presence of an ambiguity in the spin determination (or the lack of this determination) it seems too early to look for the interpretation of other states observed in the decay of ^{79}Rb.

Recollecting the above discussion one may conclude that the similarity in the structure of low-lying states in ^{79}Kr and ^{77}Se nuclei is probable. One may, however, observe some differences in the level feedings in β^+ decay in these two nuclei, resulting from the fact that in ^{77}Se the decay goes from the $3/2^-$ ground state of ^{77}Br, while the ground state of ^{77}Rb is most likely $5/2^-$.

In view of the discussed applicability of the Nilsson model to describe some properties of the ^{77}Se and ^{79}Kr nuclei it seems to be probable that these nuclei, lying beyond the stability line, may be deformed.

Further investigation is however needed in order to obtain more precise experimental information on ^{79}Kr. Gamma-gamma correlation measurements for stronger cascades, as well as life-time measurements would be a source of such information and the determination of the magnetic moments of the $7/2^+$ isomeric and $1/2^-$ ground states would provide a substantial basis for confrontation with model predictions. Some of these experiments are planned by the authors.

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