THE DECAY OF THE GROUND STATE OF ^{82}Rb

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An investigation of the decay scheme of ^{82}Rb isomer by means of a Ge(Li) detector, NaJ(Tl) counters, and coincidence techniques establishes, besides the levels 776.9 and 1475.1 keV known from the decay of ^{82}Br, levels characterized by the following energies (in keV): 1487.4, 2172.4, 2481.0, 2945.0 and 3188.0. The spins and parities to these levels are proposed on the basis of log *ft* values and disintegration modes. Furthermore, correlation experiments have been performed which furnish the 0 spin value to the 2172.4 keV level. The 1487.4 keV level is tentatively assigned to the 0^+ spin and parity.

Professor Henryk Niewodniczański our beloved master and techer, was, apart from his directorship the Head of the Nuclear Department of the Institute of Nuclear Physics, many fields of spectroscopic research being inspired by him. As a member of the Scientific Council of the Joint Institute of Nuclear Research in Dubna, he was one of the organisers of the Nuclear Spectroscopy Division in this Institute and he put much effort into developing the now fluorishing collaboration of the Cracow Institute with this international centre.

It seems to us to be appropriate to include in this commemorative issue of Acta Physica Polonica a paper on nuclear spectroscopy based on the experimental results obtained by the Cracow group of physicists at the heavy ion cyclotron of the Joint Institute.

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1. *Introduction*

The transitions in ^{82}Kr following the negaton decay of ^{82}Br ($J^{\pi} = 5^{-}$) have been studied by several investigators. Four papers on ^{82}Br by Etherton and Kelly [1], Raman [2], Hsu and Wu [3] and Liukkonen, Hattula and Anttila [4] contain very detailed information on the past and present data concerning the decay of this radioisotope. On the other hand, the information on the transitions in ^{82}Kr following the positron and/or EC decay of ^{82}Rb ($J^{\pi} = 1^{+}$) isomer gathered before the present work started, was rather scanty. Sakai *et al.* [5] and Jha *et al.* [6] examined to some extent, using scintillation counters, the decay of 25 day ^{82}Sr which decays through the 1.25 min ground state of ^{82g}Rb to the levels of ^{82}Kr. Later Vrzal *et al.* [7] used a Ge(Li) detector and observed 9 γ-rays following the decay of ^{82g}Rb (see Table I). On the basis of these transitions alone they proposed a decay scheme.

During the course of the present study [8] the work by Raman and Pinajian appeared [9] which was also concerned with the decay of ^{82g}Rb isomer. Because of some differences in the resulting level schemes of ^{82}Kr proposed in Ref. [9] and in the present work and because of some additional experiments included in the present work, such as directional correlation measurements, which helped to assign the zero spin value to the 2172.4 keV state in ^{82}Kr, the results seem worth publishing.

2. *Apparatus and source preparation*

The half-life of the ^{82g}Rb isomer is 1.3 min, which would limit experimental possibilities quite seriously. Fortunately this isomer is entirely fed in the decay of the 24 day ^{82}Sr ground state [10] and therefore all measurements can be carried out with the source of ^{82}Sr.

The ^{82}Sr activity the γ-ray spectroscopic studies was produced by bombarding a copper target with 85 MeV ^{22}Ne ions in the 300 cm cyclotron of the Laboratory of Nuclear Reactions of the JINR in Dubna, USSR.

The target was dissolved in concentrated nitric acid and strontium and rubidium carriers were added. The strontium carbonate $SrCO_3$ was precipitated from the solution and freed of copper by its dissolution in the form of an ammoniacal complex. The strontium carbonate was then carefully washed and radiochemically purified several times.

The single spectra of γ-rays were studied with a lithium-drifted germanium detector of coaxial type with an active volume of 13 cm^3. The energy resolution of the detector (FWHM) was 3.5 keV at the energy of 662 keV.

The associated electronics consisted of a preamplifier with a field-effect transistor as its first stage, a linear amplifier with double differentiation and double integration, and a biased amplifier [11, 12]. The spectra were recorded on an LP 4050–512 multi-channel pulse-height analyser.

The γ-ray coincidence studies were carried out with the Ge(Li) detector and a 5.1× ×5.1 cm NaJ(Tl) scintillation counter. The "fast-slow" coincidence circuitry, described in detail elsewhere, contained a time-to-pulse height converter, which followed by a pulse height discriminator, served as the fast coincidence circuit. Its adjustable resolving time was set at 50 nsec.

The γ—γ directional correlations were performed with the same detectors, the angle extended between them being automatically changed every 10 minutes.

3. *Experimental results*

3.1. The γ-ray single spectrum of ^{82g}Rb

The typical spectra of ^{82g} Rb are shown in Fig. 1. The spectrare vealed, besides transitions with energies 698.1, 776.9 and 1475.1 keV known from the decay of ^{82}Br, other transitions with energies 710.5, 1395.5, 1704.1, 2169.0, 2411.0, 2481.0 and 2945.0 keV. All these lines were observed to decay with the same half-life as those already assigned to ^{82g}Kr, *e. g.* the 776.9 keV line. The belief that the lines belong to the decay of the ^{82g}Rb was also supported by measurements carried out with three different sources obtained from different irradia-

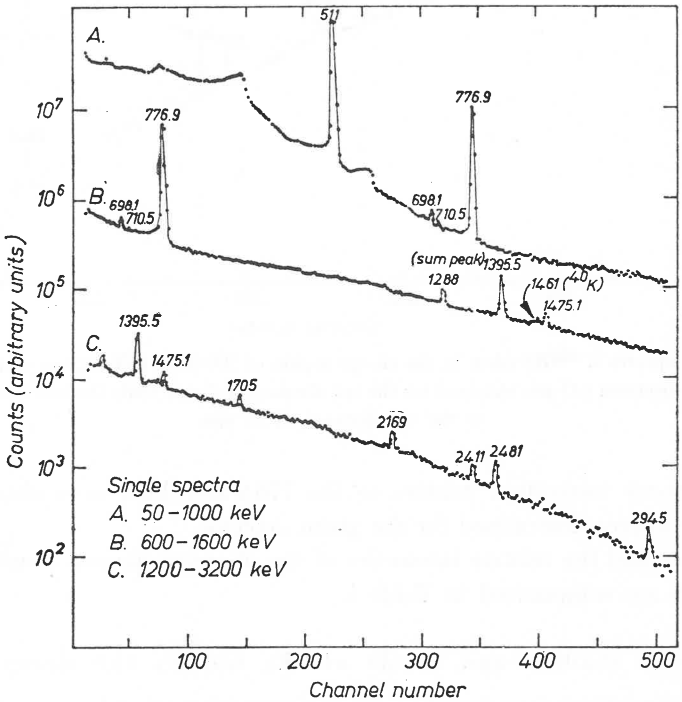

Fig. 1. Gamma-ray spectrum of ^{92g}Rb taken with a 13 cm^3 Ge(Li) detector in three energy regions: 0–1000 keV (*A*) 600–1600 keV (*B*), and 1200–3299 keV (*C*)

tions. Furthermore, the peaks at energies higher than 1200 keV were checked for summing, effects in the detector. In Fig. 2 two spectra are shown for comparison. The upper spectrum was taken at a source-to-detector distance of 8 mm and the lower one at a distance of 25 mm. It can be clearly seen that the ratio of the area under the 1288 keV peak (the sum of the energy of the 776.9 keV transition and the 511 keV energy of one of the annihilation quanta) to that under the 1395.5 keV peak decreases by a factor of about three, whereas the ratios of areas under the peaks at 1475.1, 1705.0, 2411.0 and 2945.0 keV to that under the 1395.5 keV photopeak remain unchanged.

The energies of the gammas were determined from calibration curves obtained for standard gamma rays of ^{22}Na, ^{137}Cs, ^{60}Co, ^{160}Tb and ThC″.

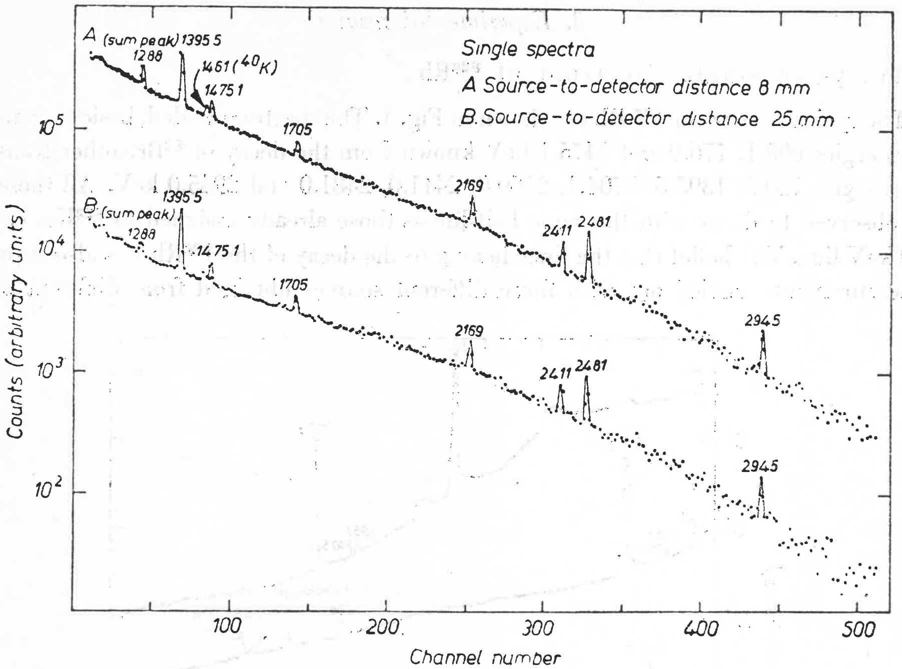

Fig. 2. Gamma-ray spectra of ^{82g}Rb taken in the energy region of 100–3500 keV for two source-to-detector distances. The upper spectrum (A) was obtained for the std distance of 8 mm while the lower one (B) corresponds to the std distance of 25 mm

The gamma-ray intensities, relative to the 776.9 keV line, were obtained from the photo-efficiency curves determined for the given detector.

The energies and the relative intensities of the observed gamma transitions from the decay of ^{82g}Rb are summarized in Table I.

3.2. Coincidence studies and levels of ^{82}Kr fed by the decay of ^{82g}Rb

The γ—γ coincidence experiments were performed for several energy gates set on the spectrum of the NaJ(Tl) scintillation counter. Besides the coincidence spectrum gated by the 776.9 keV transition, additional coincidence spectra were taken with the gates set on energy ranges 570–650 and 640–720 keV. The energy region above 1000 keV was taken as an integral energy gate in one coincidence measurement and in others the energy ranges 1210–1410, 1350–1550, 1600–1900, 1950–2250 and 2350–2550 keV were used for gating.

3.2.1. Gamma coincidences with the 776.9 keV transition

The gamma spectrum in coincidence with the 776.9 keV photopeak is shown in Figs 3a and 3b. The 776.9 keV transition is seen to be in coincidence with the 698.1, 710.5, 1395.5, 1705.0, 2169.0. and 2411.0 keV transitions. The peak at 776.9 keV is due to true coincidences of the 776.9 keV photon with compton scattered gammas of higher energy transitions, and to photons of β^+ annihilation in flight.

TABLE I

Energies and relative intensities of γ-rays from ^{82g}Rb

Present work Ge(Li)		Raman and Pinajian [9] Ge(Li)		Vrzal *et al.* [7] Ge(Li)	
Energy (keV)	Rel. intensity	Energy (keV)	Rel. intensity	Energy (keV)	Rel. intensity
698.1±0.5[a]	2.2±0.7	697.0±0.4	4.3	698±1	13.5
698.1±0.3[a]	10.0±1.0	698.4±0.2	10.4		
710.5±0.3	2.3±0.6	710.6±0.6	3.5	712±1	3.6
776.9±0.3	1000	776.5±0.2	1000	777±1	1000
1395.5±0.5	37.8±4.0	1395.2±0.3	35.3	1384±1	39.8
1476.1±1.0	6.8±0.7	1475.0±0.3	6.1	1475±1	6.3
1705.0±2.0	4.1±1.0	1702.9±0.5	3.7	1475±2	4.2
2169.0±2.0	3.5±0.8	2168.3±1.0	2.5	2162±2	3.4
2411.0±2.0	1.7±0.4	2411.7±2.0	1.2	2413±3	1.5
2481.0±2.0	2.8±0.7	2480.1±1.0	2.2	2480±3	2.2
2945.0±2.0	0.7±0.2				

[a] The doublet. For details see subsect. 3.2.2.

3.2.2. Coincidence spectra for the 550-650, 640-720, 1210-1410 and 1350-1550 keV energy gates

The coincidence spectra for the first two energy gates are compared in Fig. 4. The upper spectrum (A) was taken with the 640–720 keV gate which includes both the 698.1 and 710.5 keV peaks. The lower spectrum (B) was measured with the 550–649 keV gate which ancloses no gamma line but a part of the tail of the annihilation peak and compton scattered gammas of the 776.9 keV transition.

The 698.1 keV transition is known from the ^{82}Br decay as depopulating the 1475.5 keV state in ^{82}Kr and thus being in coincidence with the 776.9 keV photon. This also true for the decay of ^{82g}Rb, as quted in 3.2.1. On the other hand, the 698.1 keV peak in the coincidence spectrum A in Fig. 4 is too pronounced to be entirely accounted for by coincidences with the tail of the 776.9 keV photopeak included in the 640–720 keV energy gate. In this spectrum the intensity ratio of the 698.1 keV line to the 1395.5 keV line is enhanced in comparison with the same ratio in the coincidence spectrum taken with the 776.9 keV gate. Moreover, the peak at the energy of 1475.5 keV, clearly seen in the coincidence spectrum A, is absent in the spectrum B. The coincidences of the 1475.5 keV photon with the 698.1 keV photon are confirmed by two spectra in Fig. 5. From a comparison of these spectra it is seen that in the coincidence spectrum taken with the 1350–1550 keV gate, which includes the 1475.5 keV transition, the peak at 698.1 keV appears clearily, but it is absent in the spectrum B taken with the 1210–1410 keV gate. All these facts can be explained only with the assumption that the 698.1 keV peak actually consists of two lines very close in energy, one of them being in coincidence with the other as well as with the 776.9 keV line and the other being in coincidence with the 1475.5 keV line. The relative intensities of the two 698.1 keV components, calculated from the coincidence spectra, are 2.2 and 10.0 for

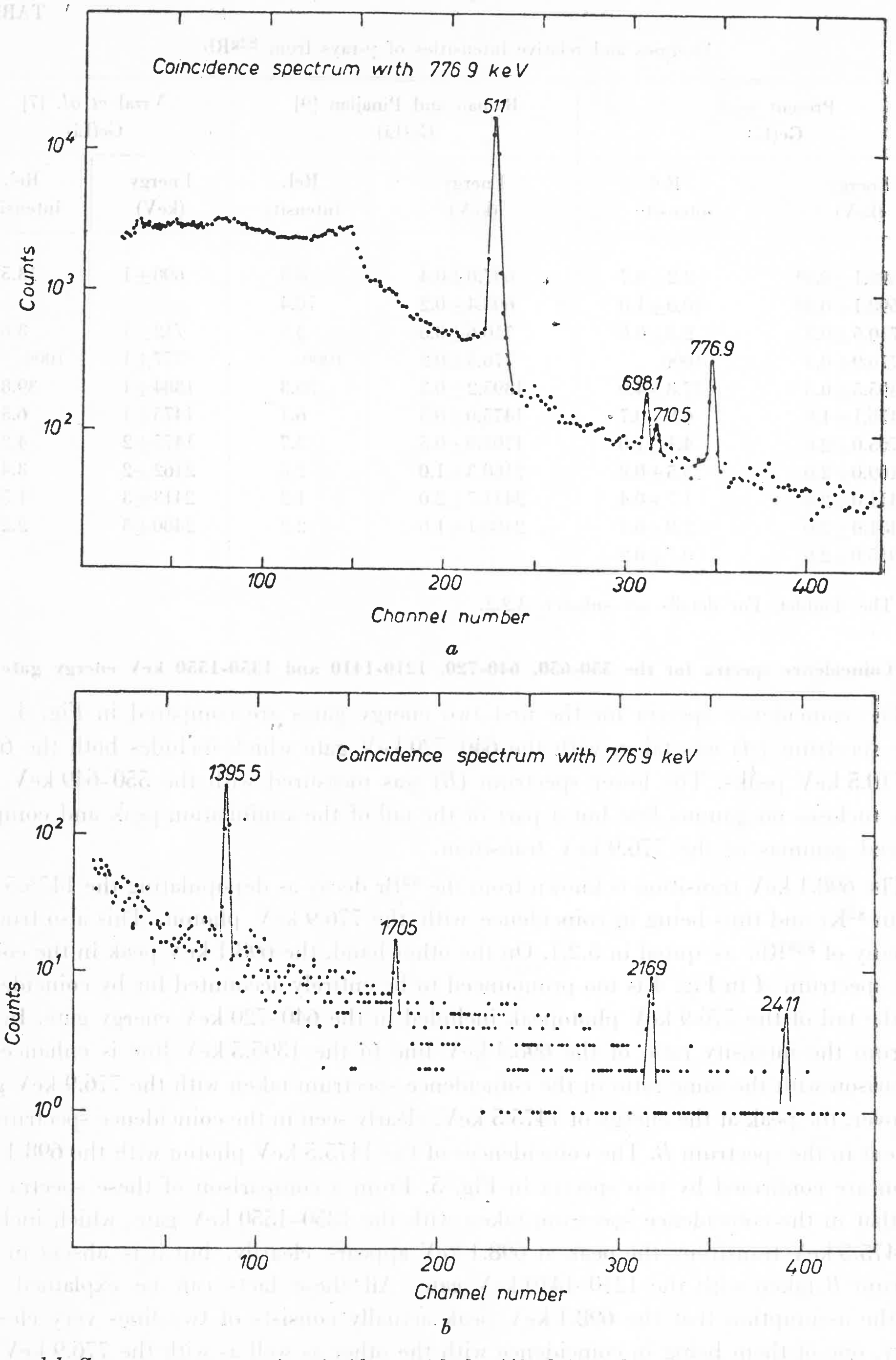

Fig. 3*a* and *b*. Gamma-ray spectrum in coincidence with the 776.9 keV peak selected by a 5.1×5.1 cm NaJ(Tl) crystal. The spectrum was observed with a 13 cm³ Ge(Li) detector in two energy regions: 50–1000 keV (Fig. 3*a*) and 100–2600 keV (Fig. 3*b*)

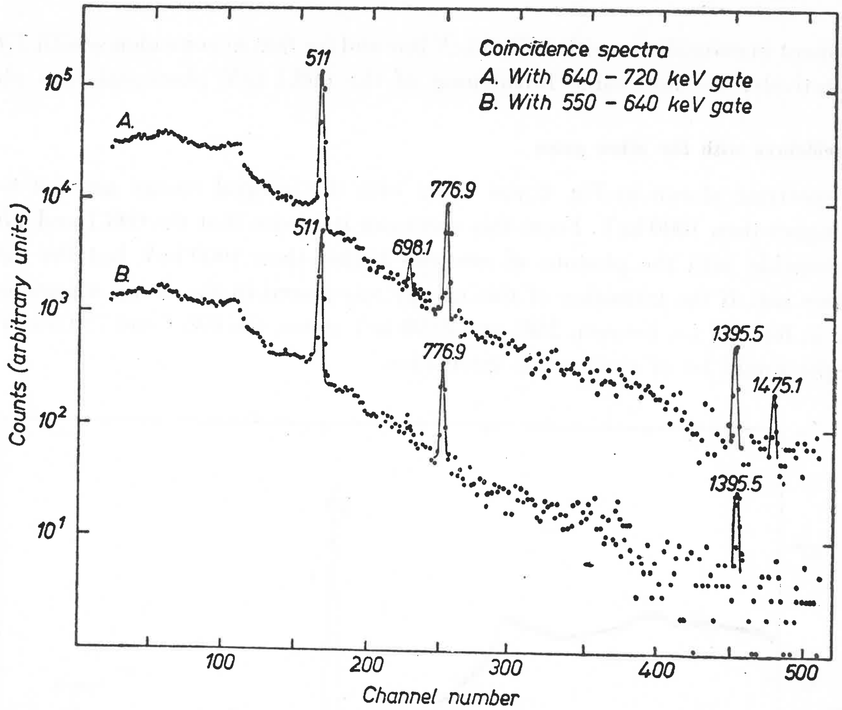

Fig. 4. Gamma-ray spectra in the energy region 50–1600 keV observed in coincidence with the 640–720 keV gate (*A*) and with the 550–640 keV gate (*B*). The detectors used were the same as those described in the caption to Fig. 3

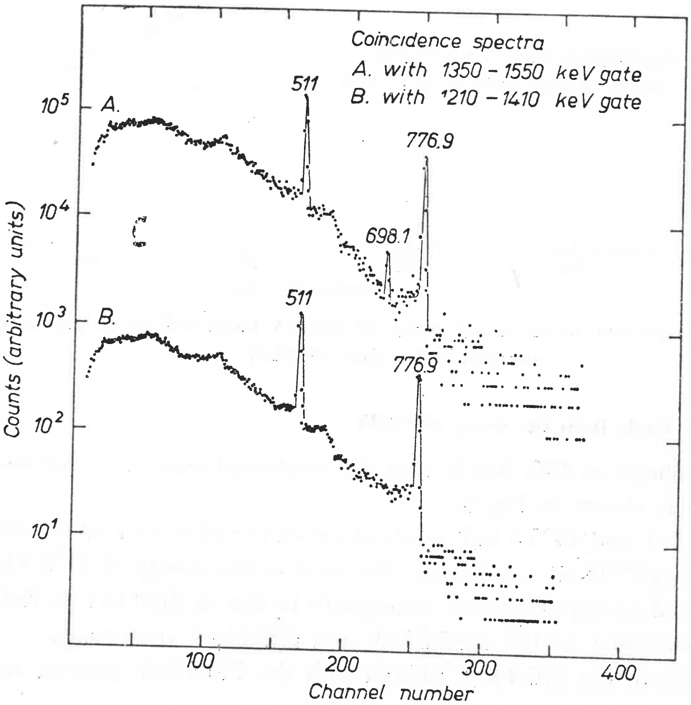

Fig. 5. Gamma-ray spectra in the energy region 50–1600 keV observed in coincidence with the 1350–1505 keV gate (*A*) and with the 1210–1410 keV gate (*B*)

the component in coincidence with 1475.5 keV line and for that in coincidence with 776.9 keV line, respectively. No noticeable broadening of the 698.1 keV photopeak was observed.

3.2.3. Coincidences with the other gates

The spectrum shown in Fig. 6 was taken with the integral energy gate set to accept energies higher then 1000 keV. From this spectrum it is seen that the 698.1 and 776.9 keV photons coincide with the photons of energies higher than 1000 keV but the 710.5 keV photon does not. If the transition of this energy was placed in the decay scheme of ^{82g}Rb as is done in Ref. [9] *i.e.* between 2481 and 3198 keV states, the 698.1 and 710.5 keV coincidence peaks would be of comparable intensities.

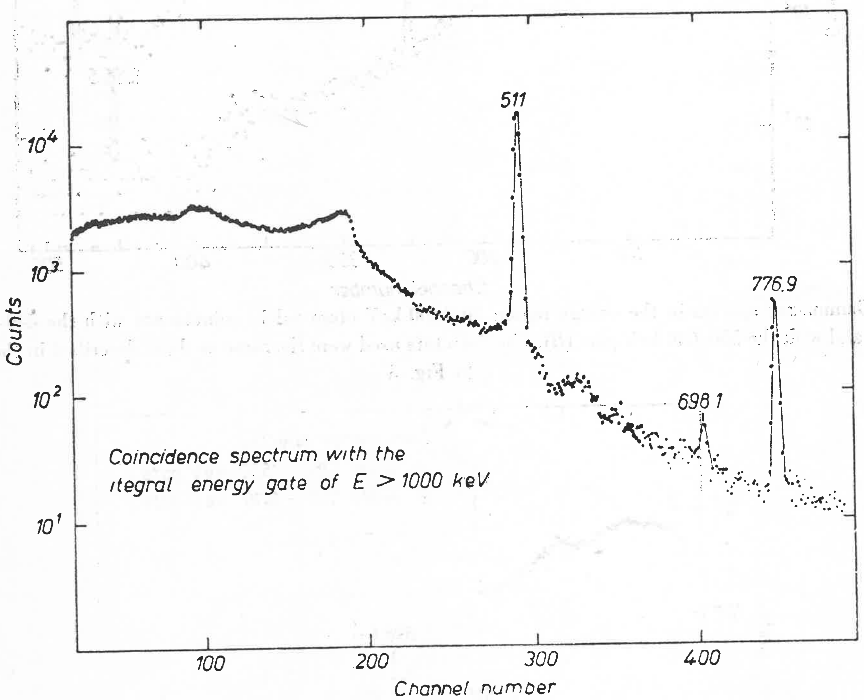

Fig. 6. Gamma-ray spectrum in the energy region 50–800 keV taken with an integral energy gate accepting energies higher than 1000 keV

3.2.4. The energy levels from the decay of ^{82g}Rb

The level scheme of ^{82}Kr based upon the single and coincidence measurements of the decay of ^{82g}Rb is shown in Fig. 8.

The 776.9 keV and 1475.5 keV levels observed in earlier work on the decay of ^{82g}Rb[5] and in the decay of ^{82}Br are confirmed. The level at the energy of 2172.4 keV determined with the improved energy resolution corresponds to that at 2190 keV in Ref. [5]. This level is actually depopulated by the 1395.5 keV and 698.1 keV transitions.

Coincidences of the 776.9 keV photon with the 710.5 keV photon, and the fact that

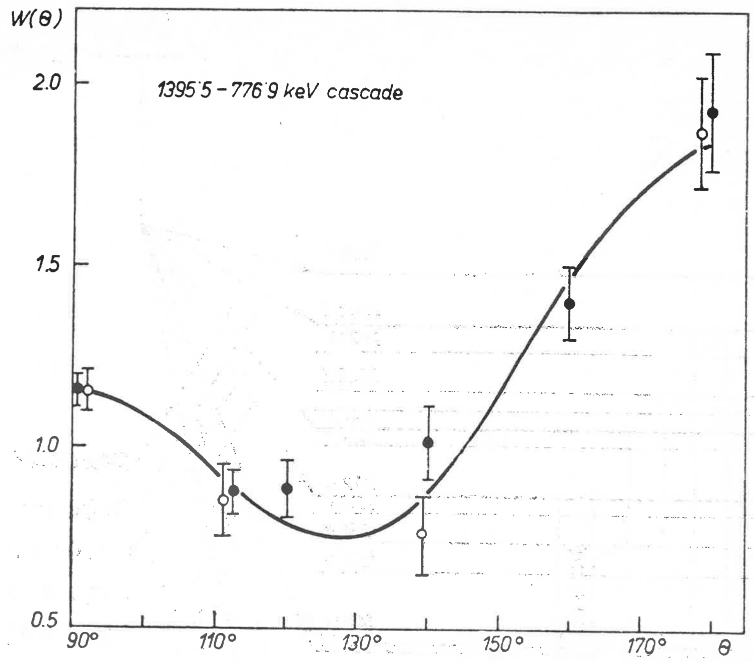

Fig. 7. Experimental function for the gamma-gamma directional correlation of the 1395.5–776.9 keV cascade in ^{82}Kr. The open circles correspond to the measurements in which the 776.9 keV photopeak was selected by the NaJ(Tl) crystal, whereas the heavy dots represent the measurement with the 1395.5 keV gate. In both cases the spectrum from the Ge(Li) detector was displayed

the latter does not coincidence with any other transition (Fig. 6) indicates the existance of a level at the energy of 1487.4 keV which is the sum of the two photon energies. No cross-over transition to the ground state was observed.

The level at the energy of 2481.0 keV was included into the decay scheme on the basis of observed coincidences between 776.9 keV and 1705.0 keV photons. The sum of these two photon energies equals, in the limits of the experimental error, the energy of the observed 2481.0 keV transition, which is put as the crossover transition to the ground state of ^{82}Kr.

The level at 2945.0 keV was introduced in a similar way. However, the only evidence for the 3188.0 keV level is given by coincidences of the 776.9 keV photon with the 2411.0 keV photon.

4. *Directional correlation measurements*

The directional correlation was measured for the $\gamma-\gamma$ 1395.5–776.9 keV cascade with the aim of identifying the spin of the 2172.4 keV state. In the earlier work by Sakai *et al.* [5] it was found that the A_4 correlation coefficient was equal to *ca.* 0.8. The authors of this reference used two NaJ(Tl) crystals in their correlation experiments, which makes the interpretation of the results rather difficult. The annihilation in fight of positions and the internal bremsstrahlung results in a relatively high gamma radiation background.

In the present work the directional correlation measurements were performed with

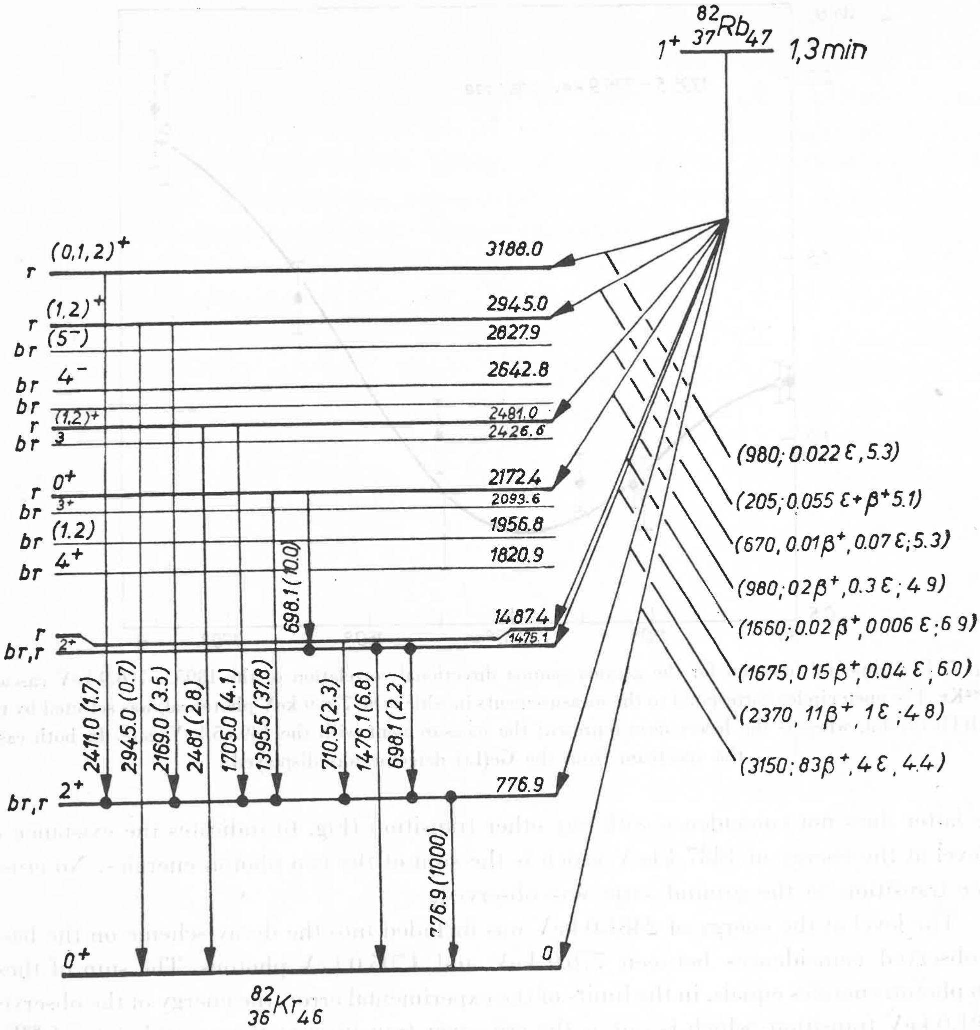

Fig. 8. The energy levels of ^{82}Kr. All energies are in keV. The heavy dots indicate coincidences. The subscripts at the levels of the left have the following meaning: *br* — levels observed in ^{82}Br and ^{82m}Rb decays [4], *r* — levels observed in the ^{82g}Rb decay (present work). In brackets to the right energy, branching of β^+ and/or *EC* decay and log *ft* are given

a Ge(Li) detector, its coincidence spectra being displayed in the two parts of the memory of the multichannel analyser, respectively to the angle between the detectors; one of the transitions in the 1395.5–776.9 keV cascade was gated by the NaJ(Tl) counter.

The measurement was automatically performed for different pairs of angles, *i.e.* the angle of 90° was combined with every other angle from the following: 112.5°, 120°, 140°, 160° and 180°. Every pair of numbers of coincidences was normalized by single counts measured simultaneously in the NaJ(Tl) channel and, furthermore, by the numbers of coincidences for the angle of 90°.

Two independent measurements of the directional correlation were carried out, one with the gate at the first transition of the 1395.5–776.9 keV cascade and the other with the gate at the second transition. This might help to avoid a systematic error which could be made by a wrong background substraction when the 776.9 keV transition was observed, and the gate was set at the 1395.5 keV energy. In this case, as has been mentioned before, true coincidences of the 776.9 keV photon with the gammas of position annihilation in flight and compton scattered photons of higher energy could effect the measured angular correlation. Nevertheless, a separate measurement was done with the energy gate set just above the 1395.5 keV photopeak, which provided the number of unwanted coincidences with the background under the 1395.5 keV peak.

In Fig. 7 the experimentally determined angular correlation curve is shown. The open circles in this figure represent the results obtained with the 776.9 keV gate, whereas the black points correspond to the case of the 1395.5 keV transition being gated (corrected for the γ(background) — γ(777 keV) coincidences, mentioned above). The full curve is the least--square fit to the experimental points and the result is as follows:

$$W = 1+(0.30\pm0.09)P_2(\cos\theta)+(1.25\pm0.25)P_4(\cos\theta). \quad (1)$$

The directional correlation coefficients A_2 and A_4 in Eq. (1) were corrected for the geometry of the set-up.

It should be mentioned at this point that because of the lack of calculated geometry correction factors for Ge(Li) detectors of the coaxial type, these were obtained experimentally from measurements of the well-known directional correlation functions for the 1173–1332 keV cascade in ^{60}Co, for cascades in ^{182}Ta, ^{160}Tb and ^{169}Yb, and were compared with tabulated Q_2 and Q_4 values for NaJ(Tl) scintillation counters of similar sizes.

The A_2 and A_4 correlation coefficients experimentally determined for the 1395.5–-776.9 keV cascade in ^{82}Kr uniquely determine the spin sequence 0 (2) 2 (2) 0, for which the theoretical correlation coefficients A_2 and A_4 are equal to 0.36 and 1.14, respectively.

5. *Discussion*

The proposed decay scheme of ^{82g}Rb based upon the experimental results outline above is shown in Fig. 8. It accounts for all the observed gamma-rays. Beside the known levels from the ^{82}Br decay at 776.9 and 1475.5 keV new levels at the energies of 1487.4, 2172.4, 2481.0, 2945.0 and 3188.0 keV are proposed on the basis of the coincidence measurements and gamma-ray energy sums. This decay scheme is in an agreement with that proposed by Raman and Pinajin [9] except for the placements of the 710.5 and 2945.0 keV transitions. As was stressed in the course of the present work, the 710.5 and 776.9 keV transitions were found to be in coincidence and no coincidences of 710.5 keV were observed with any other γ-ray.

The logft values and β^+ and/or EC branchings, shown to the right in Fig. 8 have been evaluated on the basis of the relative intensities of gamma-rays and the proposed decay scheme (the branching to the ground state of ^{82}Kr was taken from Refs [5] and [7]), and taking the theoretical f_+/f_ε ratios. The Q^+ value was assumed to be 4170 ± 30 keV [13]. Internal conversion was not taken into account since it is expected to be negligible.

Starting from the 1^+ spin and parity of the ^{82g}Rb ground state the examination of the log *ft* values suggests the values of spin and parities for the proposed levels. The 2481.0, 2945.0, and 3188.0 keV excited states are probably restricted to a spin-parity of 0^+, 1^+, 2^+. However, in the cases of the 2481.0 and 2945.0 keV states the zero spin values are excluded by the gamma-rays directly connecting these states with the ground state (0^+). The limited information currently available, makes it impossible to say anything more precise about the nature of these states.

The directional correlation experiment and log *ft* value of β decay to the 2172.4 keV state establish unambiguously the 0^+ spin and parity assignments for this state. It seems, however, very doubtful whether this level may be interpreted as a member of the two-phonon vibrational triplet in the case of a simple vibrational model. Its energy is almost three times as high as the energy of the first excited 2^+ state. Moreover, the beta decay to this state is of a rate comparable to that of the decay to the 0^+ ground state of ^{82}Kr.

A more probable candidate for the 0^+ two phonon vibrational state in ^{82}Kr might be the 1487.4 keV state, introduced in the present work. Three considerations seem to support this suggestion: 1) In Fig. 9 are shown the level schemes of ^{80}Kr and ^{82}Kr. The spins of the second and third excited states in ^{80}Kr were determined from directional correlations experiments of Ramayya *et al.* [14], and their positive parities were assigned according to the 5.5 and 5.6 log *ft* values for the decay of the 1^+ ground state of ^{80}Rb to these states, respectively [15]. In Fig. 9 it is seen that the 1475.1, 1487.4 keV doublet in ^{82}Kr lies at an

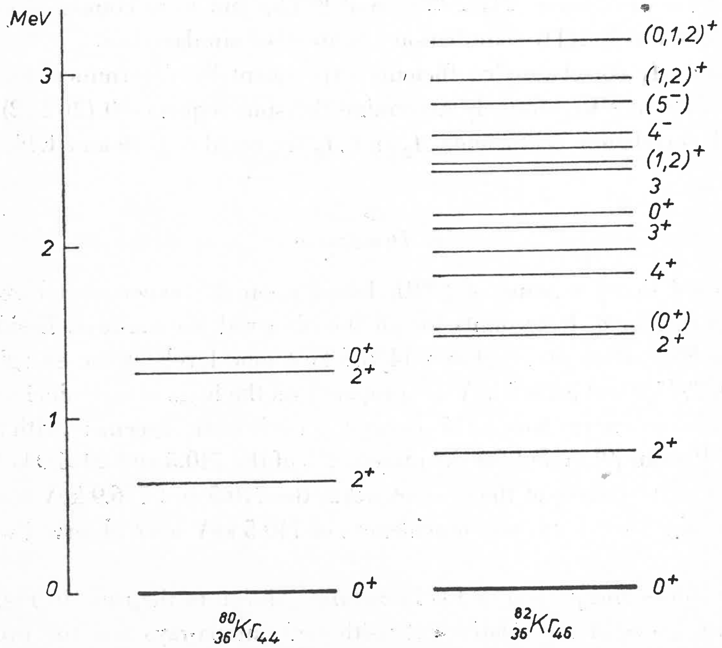

Fig. 9. Comparison of the energy level schemes of ^{80}Kr and ^{82}Kr

energy comparable to the $2'^{+}$, $0'^{+}$ doublet in two-neutron-defficient ^{80}Kr. 2) In Refs [16] and [17] it is reported, that in a few known cases the beta decay from the 1^{+} spin-parity states in odd-odd nuclei to the $2'^{+}$ and $0'^{+}$ in even-even is hindered, compared with the decay to the 0^{+} ground and 2^{+} one phonon states in these nuclei. A similar tendency is observed in the decay of ^{80}Rb and is expected to hold in the decay of ^{82}Rb. 3) The centre of gravity of the 1475.1, 1487.4 and 1820.9 keV states (the latter being the 4^{+} state observed in the decay of ^{82}Br and ^{82m}Rb [4]) lies at an energy nearly twice as high as the energy of the first excited 2^{+} state in ^{82}Kr.

The above remarks, which are, of course, far from being a direct proof, might impose tentative assignments of the 0^{+} spin and parity to the 1475.1 keV state in ^{82}Kr. But the problem remains open and the spin value for this level is still to be directly established.

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