Экз. чит. зала

СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ
Дубна

E6 - 4360

R.Broda, A.Z.Hrynkiewicz, J.Styczeń,
Z.Szeglowski, W.Waluś

HIGH RESOLUTION SPECTROSCOPIC STUDY OF THE DECAY OF THE ^{82m}Rb AND ^{82g}Rb ISOTOPES

ЛАБОРАТОРИЯ ЯДЕРНЫХ РЕАКЦИЙ

1969

E6 - 4360

R.Broda, A.Z.Hrynkiewicz, J.Styczeń,
Z.Szeglowski, W.Waluś

HIGH RESOLUTION SPECTROSCOPIC STUDY OF THE DECAY OF THE ^{82m}Rb AND ^{82g}Rb ISOTOPES

Научно-техническая
библиотека
ОИЯИ

1. Introduction

The transitions in ^{82}Kr following the negaton decay of ^{82}Br have been studied by several investigators during the past 27 years. Three papers on ^{82}Br by Etherton and Kelly /1/, Raman et al. /2/, and Hsu and Wu /3/ contain a very detailed information on the past and present results on this radioisotope. On the other hand, there is scarce information on the transitions in ^{82}Kr following the position and/or EC decay of ^{82m}Rb and ^{82g}Rb.

In 1962 Sakai, Ikegami and Yamazaki /4/ examined to some extent the spectra accompanying 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. Since then no detailed investigations have been performed.

The ground state spin of ^{82g}Rb is considered to be 1+, whereas the spin of the metastable state of this nucleus is believed to be 5– /5/, the same as the spin of the ground state of ^{82}Br. Consequently population of the excited states of ^{82}Kr from the decay of ^{82m}Rb has been expected to be similar to that from the decay of ^{82}Br, but levels observed from the decay of ^{82g}Rb should be different. Therefore it seemed desirable to investigate the energy spectra with Ge(Li) detectors, Ge(Li)–NaJ(Tl) coincidences, and directional correlations which might throw more light on the level structure of the ^{82}Kr nucleus.

2. *Apparatus and Source Preparation*

The ^{82}Sr activity for 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. From the solution the strontium carbonate $SrCO_3$ was precipitated 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 rubidium acitivity was obtained from the solution after the separation of the strontium. The solution was evaporated and the dry precipitate dissolved in hydrochloric acid. From this the copper was removed by precipitation in the form of copper sulphide. Then ammonium salts were removed and the rubidium was precipitated as rubidium tetraphenylboron.

The single spectra of γ-rays were studied with a lithium-drifted germanium detector of coaxial type with an active volume of 13cm^3. The energy resolution of the detector (FWHM) was 3.5 keV at the energy of 662 keV of ^{137}Cs). This resolution was obtainable at fairly low counting rates up to ca 5x10^3 per sec and with single integration of the pulses. At higher counting rates of 3x10^4 pulses/sec, necessary in some coincidence studies, double differentiation had to be used, with which the resolution was 5 keV at 662 keV energy.

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/6,7/. 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 5.1x5.1 cm NaJ(Tl) scintillation counter. The "fast-slow" coincidence circuitry, described in detail elsewhere/7/, contained a wide band fast amplifier with a "leading edge" tunnel diode in the output stage. The pulses from the fast amplifier fed a time-to-pulse height converter at one input and pulses from the RCA 6810A photomultiplier at the other. The TPH-converter, together with a pulse height discriminator, served as the fast coincidence circuit. Its resolving time could be adjusted and 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 single γ-ray spectra were measured with the Ge(Li) detector in three energy ranges from 0-1000 keV, from 650-1700 keV, and from 1250-3200 keV. The typical spectra for these energy regions are shown in Fig.1. The spectra revealed, beside known transitions with energies 698.1 keV, 776.9 keV, 1475.1 keV and 1395.5 keV (in Ref./4/ an assignment of 1410 keV was given to the last), weak peaks at 710.5 keV, 1704.1 keV, 2169 keV, 2411 keV, 2481 keV and 2945 keV. These peaks were observed to decay with the same half-life as the 776.9 keV peak and the others already assigned to the ^{82}Kr . The belief that the new lines belong to the decay of the ^{82g}Rb was also supported by measurements carried out with three different sources obtained from different irradiations. 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 777 keV transition with the 511 keV energy of one of the annihilation quanta) to that under the

1395 keV peak decreases by a factor of three, whereas the ratios of areas under the peaks at 1475 keV, 1704 keV, 2411 keV and 2945 keV to that under the 2395 keV photopeak remain unchanged.

The energies of the gammas were determined from calibration curves obtained for well-known gamma rays of ^{22}Na, ^{137}Cs, ^{60}Co, ^{160}Tb and ThC″. Least-square fits were performed to the positions of peaks for different gain settings and different biases of the biased amplifier. The nonlinearly of the set-up for the energy range from 0-1000 keV was less than 0.3 keV and less than 0.5 keV for higher energies.

The gamma-ray intensities, relative to the 777 keV line, were calculated using photo-efficiency curves measured for the detector.

The energies and the relative intensities of the observed gamma transitions are summarised in Table 1.

3.2. Coincidence studies and level energies from the decay of ^{82g}Rb

The γ-γ coincidence experiments were performed for several energy gate settings on the spectrum of the NaJ(Tl) scintillation counter. Beside the coincidence spectrum with the 776.9 keV transition accepted in the gate, additional coincidence spectra were measured in separate experiments with the gate set on energy ranges from 570-650 keV and from 640-720 keV. The energy region above 1200 keV was devided into some segments and the coincidence gate set on ranges 1210-1410 keV, 1350-1550 keV, 1600-1900 keV, 1950-2250 keV and 2350-2550 keV.

3.2.1. Gamma coincidences with 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 photon is seen to be in coincidence with the 698.1, 710.5, 1395.5, 1705, 2169 and 2411 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.

3.2.2. Coincidences with the 550-650 keV, 640-720 keV, 1210-1410 keV and 1350 -1550 keV energy segments

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

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 is also true for the decay of ^{82g}Rb, as quoted in 3.21. On the other hand, the 698.1 keV peak in the coincidence spectrum A in Fig.4 is too pronounced to be accounted for by coincidences with the tail of the 776.9 keV photopeak included in the 640-720 keV energy gate. The ratio of the area under the 698.1 keV peak to that under the 1395.5 keV peak is enhanced in comparison to the ratio for the coincidence spectrum taken with the 776.9 keV gate. Moreover, the peak at the energy of 1475.5 keV is clearly seen in the coincidence spectrum A, whereas no peak is observed at this energy in the spectrum B. The coincidences between the 1475.5 keV photon and the 698.1. keV photon are confirmed by two coincidence spectra in Fig.5. From a comparison of these spectra it is again seen that in the coincidence spectrum taken with the 1350-1550 keV gate , which includes the 1475.5 keV transition, the peak at the 698.1 keV energy appears in the coincidence (but not in the spectrum B). These facts can be explained only with the assumption that the 698.1 keV peak actually consists of two photons very close in energy, one of them being in coincidence with the other as well as with the 776.9 keV photon and the other being in coincidence with the 1475.5 keV photon. The relative intensities of the two 698.1 keV components were calculated from the coincidence spectra to be 0.2 for that in coincidence with the

1475.5 keV photon and 1.0 for the other. No noticeable broadening of the 698.1 keV photopeak was observed.

3.2.3. The coincidences with the other gates

The spectra shown in Fig.6 were taken with the energy gate settings at energy ranges 1600-1900 keV, 1950-2250 keV and 2350-2550 keV, respectively. From these spectra the 776.9 keV photon is confirmed as being in coincidence with the 1705, 2169 and 2411 keV photons enclosed in the respectively gates.

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

On the basis of the single spectra and coincidence measurement of the decay of ^{82g}Rb , outlined above, four new excited states were introduced into the level scheme of ^{82}Kr .

The 776.9 keV and 1475.5 keV levels observed in earlier work /3/ on the decay of ^{82g}Rb and in the decay of ^{82}Br are confirmed. The level at the energy of 2172.4 keV corresponds to that at 2190 keV in Ref./3/ with the improved energy determination. This level is actually depopulated by the 1395.5 keV and 698.1 keV transitions.

According to coincidences of the 776.9 keV photon with the 710.5 keV photon, the latter was not observed to coincide with any other transition, a level at the energy of 1487.4 keV was introduced which was the sum of the two photon energies. No cross-over transition to the ground state was observed.

The level at the energy of 2481 keV was put into the decay scheme on the basis of observed coincidences between 776.9 keV and 1704 keV photons. The sum of these two photon energies equals, in the limits of the experimental error, to the energy of the observed 2481 keV transition, which was put as the crossover transition to the ground state of ^{82}Kr .

The level at 2945 keV was introduced in a similar way. However, the only evidence for the 3188 keV level is given by coincidences of the 776.9 keV photon with the 2411 keV photon.

3.3. The decay of ^{82m}Rb

The spin of the metastable state of the ^{82}Rb nucleus is believed to be 5$^-$/5/, the same as the spin of the ground state of ^{82}Br. The strongest transitions observed from the decay of ^{82m}Rb have been calculated to have similar relative γ-ray intensities as those from the decay of ^{82}Br /5/. But no detailed study of gamma radiation has been noticed in the literature so far.

In the present work the decay of the metastable state of the ^{82}Rb nucleus was studied to a certain extent, by single gamma and some gamma-gamma coincidence measurements, using two detectors in the "fast-slow" coincidence set-up.

The typical single γ-ray spectrum is shown in Fig.7 . It contains peaks belonging to the decay of ^{82m}Rb and also those from the ^{81}Rb decay. Both these isotopes were produced in the target during irradiations with ^{20}Ne heavy ions.

To separate transitions of ^{82m}Rb (6.4h) from those of ^{81}Rb (4.7h), the half-lives of all the gamma rays were followed. Moreover, from similar irradiation, a pure source of ^{81}Rb was produced by extraction of the strontium activity, from which, two hours later, the rubidium activity was separated. With this source the gamma transitions from the ^{81}Rb decay were examined.

The measured γ-rays of ^{82m}Rb and their relative intensities are summarised in Table 2. In the third column of this table the intensities of gamma-rays of the decay of ^{82}Br /2,3/are given for comparison. It is seen that there is a great similarity between the relative intensities of the gamma transitions from the ^{82}Br and ^{82m}Rb decays apart from the intensity of the 1008 keV γ-ray, which is six times stronger in the ^{82m}Rb decay. The photopeak of the 138 keV transition was masked by back-scattering peaks from the strong 190keV transition of ^{81}Rb and therefore not seen in the spectra, whereas the 1955 keV gamma-ray could not be clearly identified owing to relatively poor statistics in this measurement.

The single γ-ray spectra together with some coincidence spectra taken with the help of two Ge(Li) detectors, support the decay scheme for ^{82m}Rb as that accepted for ^{82}Br which is shown to the left in Fig.8. The branching ratios, calculated from γ-ray intensities for the decay of ^{82m}Rb to the 2648 keV state and to the 2828 keV state are 91% and 8%, respectively.

4. *Directional Correlation Measurements*

The directional correlation was measured for the 1395-777 keV cascade with the aim of identifying the spin of the 2172.4 keV state. In the earlier work by Sakai et al./3/ it was found that the A_4 correlation coefficient was equal to about 80%. 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 flight of positions and the internal bremsstrahlung results in a relatively high gamma radiation background.

The using of a lithium-drifted Ge(Li) detector in directional correlation measurements involves, in some cases, less statistics but on the other hand the photopeaks are well-resolved and the background under a given peak can be estimated from both sides of it and subtracted.

In the present work the directional correlation measurements were performed with 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 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°. All the pairs of numbers of coincidences were 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

1395-777 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 subtraction when the 777 keV transition was observed and the gate was set at the 1395 keV energy. In this case, as has been mentioned , true coincidences of the 777 keV photon with the gammas of position annihilation in flight and compton scattered photons of higher energy transitions could effect the measured angular correlation. Nevertheless, a separate measurement was done with the energy gate set just above the 1395 keV photopeak, which provided the number of unwanted coincidences with the background under the 1395 keV peak.

In Fig.8 the experimentally determined angular correlation curve is shown. The open circles in this figure represent the measurement with the 777 keV gate, whereas the black points correspond to the case of the 1395 keV transition being gated (and these are 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:

$$W(\theta) = 1 + (0.30 \pm 0.09) P_2 (\cos\theta) + (1.25 \pm 0.25) P_4 (\cos\theta). \qquad (1)$$

The directional correlation ciefficients A_2 and A_4 in/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 cascade 1173-1332 keV in ^{60}Co, for cascades in ^{182}Ta and ^{160}Tb and ^{169}Yb, and were compared with 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 1395-777 keV cascade in ^{82}Kr were compared with the theoretical ones for spin sequences I-2^{+}E2 -0^{+}. The agreement is obtained when the spin sequence is $0^+ \xrightarrow{E2} 2^+ \xrightarrow{E2} 0^+$, 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 outlined above, is shown in Fig.9. on the right and accounts for all the observed gamma-rays. This decay scheme is compared with that of ^{82m}Rb and ^{82}Br shown on the left in Fig.9. Beside known levels at 776.9 keV and 1475.5 keV, new ones at the energies of 2172.4 keV (as has been pointed out, this level corresponds to the 2190 keV level in Ref./4/), 1487.4 keV, 2481 keV, 2945 keV and 3188 keV are proposed, according to the coincidence measurements and gamma-ray energy sums.

The log ft values and β^+ and / or EC branchings, shown to the right in Fig.9, have been evaluated on the basis of the relative intensities of gamma-rays and the proposed decay scheme (the β^+ branching to the ground state of ^{82}Kr was taken from Ref./4/). Examination of the log ft values and 1^+ spin and parity of the ^{82g}Rb ground state indicate probable values of spins and parities for the new levels introduced in this work.

The 3188, 2945 and 2481 keV levels are probably restricted to a spin of 0,1,2^+, however, in the case of 2945 and 2481 keV levels the zero possibility for the spin must be excluded. The gamma-rays of 2945 and 2481 keV directly connect this states with the ground state (0^+), thus leaving only 1 or 2 spin assignments possible for the both levels. The limited information, presently available, makes it impossible to say more precisely about the nature of these states.

The high log ft value for the β -transition to the 1487 keV level admits the positive or the negative parity for this state, but the experimental information is too scarce to suggest any spin value.

The angular correlation measurement established unambiguously 0^+ spin and parity for the 2172.4 keV level. It seems to be very doubtful to interprete this state as a part of the two-photon triplet of states in the case of vibrational model, because its energy is much too high in comparison with the prediction of this model.

The two lowest states 2^+ as well as all the other states observed in the decay of the metastable ^{82m}Rb have the spins established by the previous studies of the ^{82}Br decay (Ref./2/). These levels have been interpreted as the excited states predicted by the asymmetrical rotor model with rotation-vibration interaction.

The authors wish to thank Professor Flerov G.N. for enabling them to work in his Laboratory and for his interest in this work.

References

1. *R.C. Etherton and L.H.Kelly. Nucl. Phys., 84,129 (1966).*
2. *S.Raman. Nucl. Phys., A90, 508 (1967).*
3. *F.H.H.Hsu and C.S.Wu. Nucl. Phys., A94, 205 (1967);*
4. *M.Sakai et al., J. Phys. Soc. Japan, 17, 1087 (1962).*
5. *Nuclear Data Sheets , B 1-4 (1966).*
6. *G.Zapalski and T.Walczak. V Symposium on Nucl. Radioelectronics, Alushta, 134 (1968).*
7. *T.Walczak et al., Reprint 13-4025, Dubna (1968).*

Received by Publishing Department
on March 18, 1969.

Table 1

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

Energy keV	Relative γ-ray intensity x/
698.1 ± 0.3	1.2
710.5 ± 0.3	0.2
776.9 ± 0.3	100.0
1395.5 ± 1.0	3.8
1475.1 ± 1.0	0.7
1705 ± 2.0	0.4
2169 ± 2.0	0.35
2411 ± 2.0	0.17
2481 ± 2.0	0.3
2945 ± 2.0	0.7

x/ 10% error on the relative intensities.

Table 2

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

Energy keV	Relative intensity (our work) x/	Relative intensity (Ref.2).
94	0.007	0.0043
138	–	0.0011
222	0.029	0.0280
274	0.006	0.0071
554	0.820	0.81
609	0.037	–
618	0.470	0.55
698	0.280	0.29
777	1.000	1.000
828	0.290	0.27
951	0.015	0.005
10 08	0.094	0.016
1044	0.420	0.38
1081	–	–
1318	0.33	0.38
1475	0.22	0.24
1659	0.015	0.01
1780	0.002	0.002
1953	–	0.0007

x/ 10% error on the relative intensities.

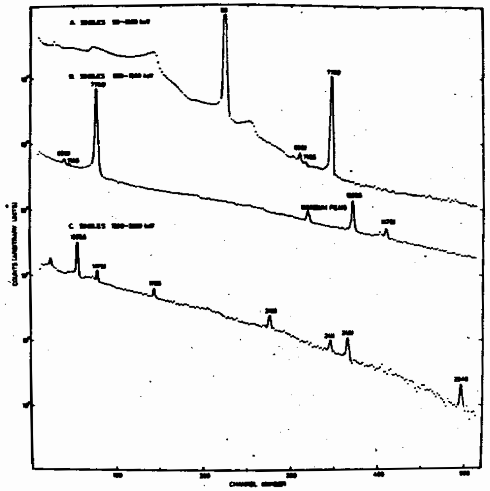

Fig.1. Gamma-ray spectrum of ^{82g}Rb taken with a Ge(Li) detector in the energy region 50-1000 keV/A/, 600-1600 keV/B/ and 1200-3200 keV/C/.

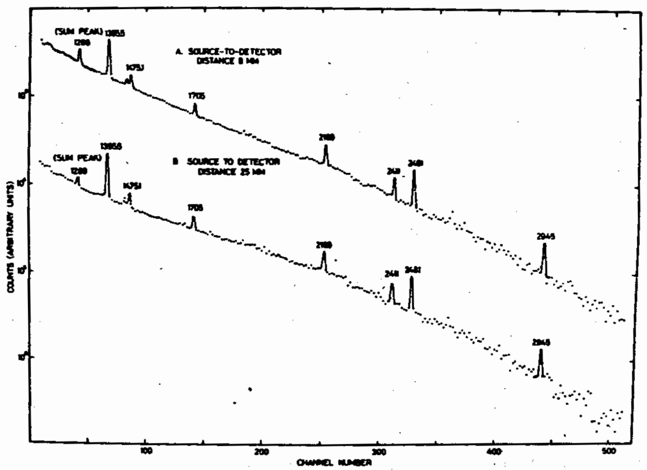

Fig.2. Gamma-ray spectrum of ^{82g}Rb taken with a Ge(Li) detector in the region 1000-3500 keV.
The upper curve was obtained with a source-to-detector distance of 8 mm. The lower curve corresponds to a source-to-detector distance of 25 mm.

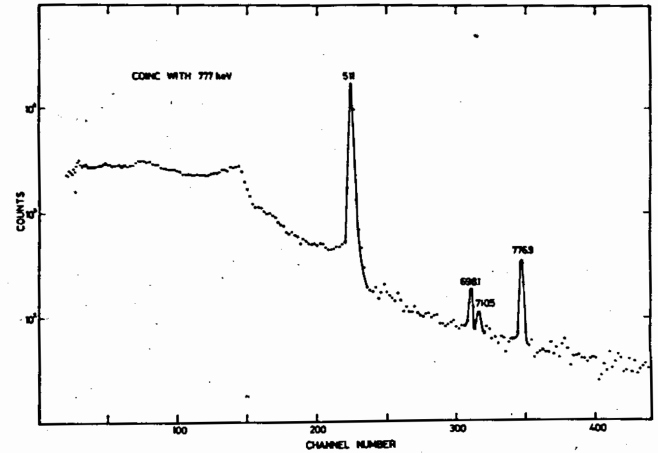

Fig.3a

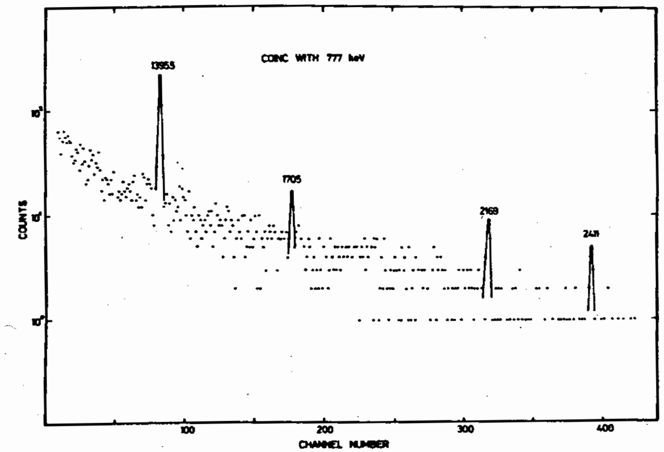

Fig.3b

Gamma-ray spectrum in coincidence with the 777 keV peak taken with the 13 cm^2 Ge(Li) and 5.1 by 5.1 cm NaJ(Tl) detectors.

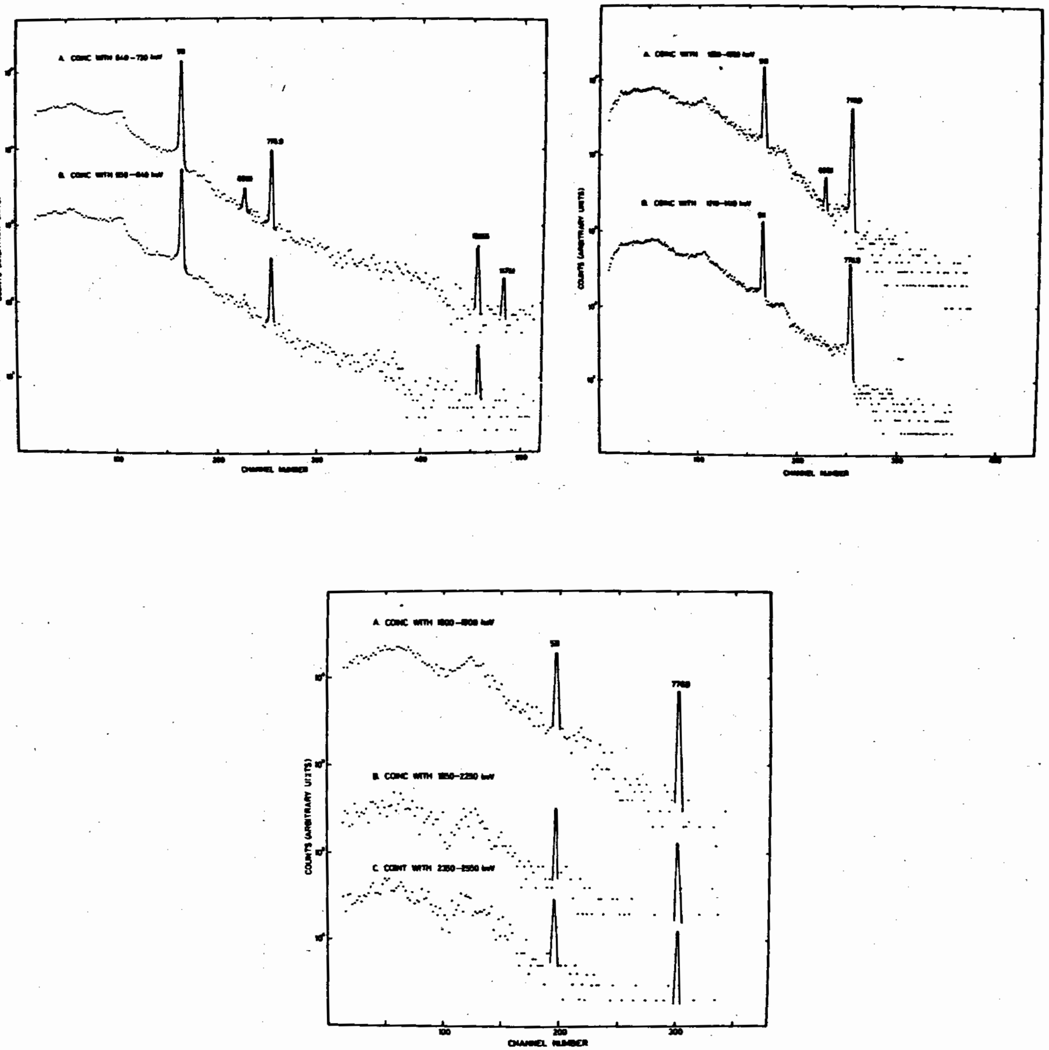

Fig.4,5,6. Gamma-ray spectra in coincidence with various segments of the 550-2550 keV region. The detectors were the same as used in Fig.3.

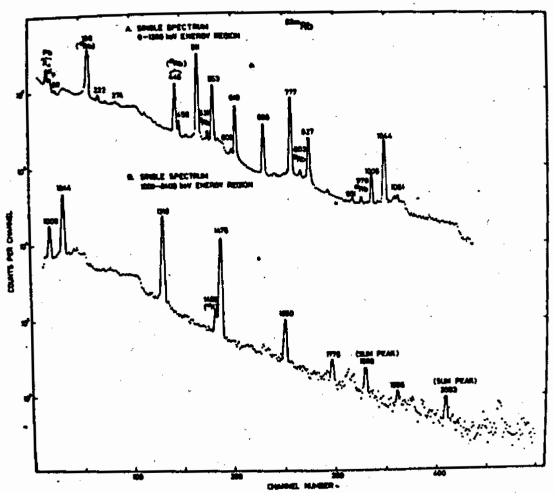

Fig.7. Gamma-ray spectrum of ^{82m}Rb taken with a Ge(Li) detector in the energy region 0-1300 keV/A/ and 1000-2400 keV/B/.

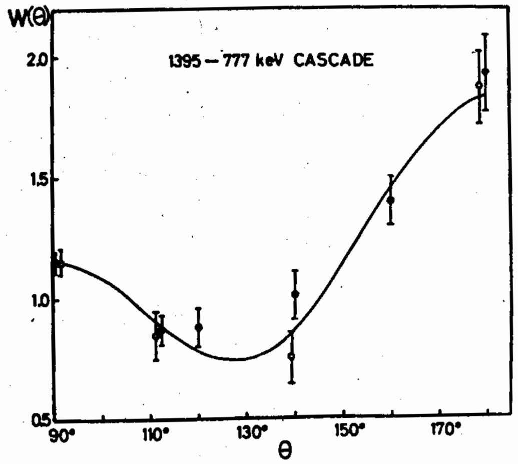

Fig.8. The gamma-gamma directional correlation of the 1395-777 keV cascade.

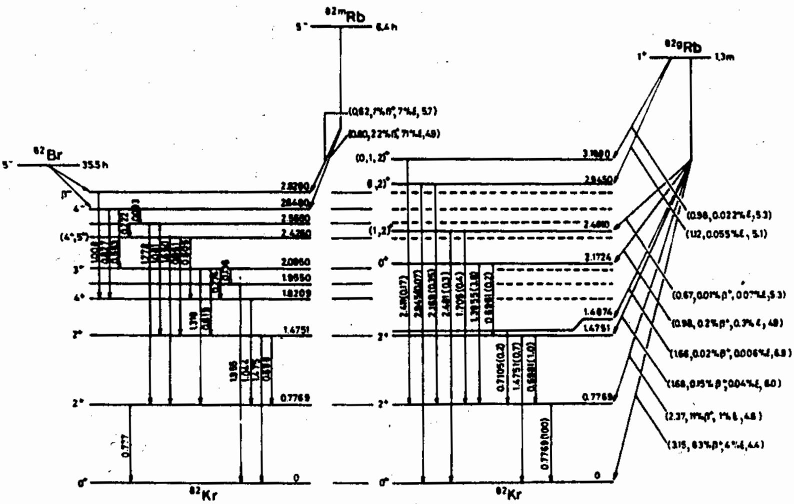

Fig.9. The proposed decay scheme for ^{82g}Rb .