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ЛАБОРАТОРИЯ ЯДЕРНЫХ РЕАКЦИЙ

STUDIES IN THE DECAY OF 29-MIN ^{81}Sr

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1. Introduction

There was a very scarce experimental information on the decay of ^{81}Sr and on levels of ^{81}Rb when this investigation was started. The evidence of the ^{81}Sr isotope with its ground state half-life of 29 min and the evidence of the metastable and ground-states of ^{81}Rb nucleus with their half-life of 30 min and 4.7 h and spins $9/2^+$ and $3/2^-$ suitably, were the only ones contained in literature/1/.

The growing interest of theoretical physicists in the region of Br , Kr , Rb and Sr nuclei encourages to experimental studies on the isotopes of these elements. The recently published work of Scholz and Malik/2/ contains their calculation in this region of nuclei. In particular these authors have computed spectrum of ^{81}Rb in function of deformation which is assumed in their model.

The purpose of this article is to present the first experimental results of our investigation of the excited states of ^{81}Rb in the decay of ^{81}Sr .

The gamma ray single spectra and $\gamma-\gamma$ -coincidence studies made it possible to construct the complex decay scheme.

The low-energy levels fed by positron decay were determined by means of a tripple coincidence experiment.

2. *Experiment*

2.1. Source preparation

The ^{81}Sr activity for γ -ray spectroscopic studies was produced by bombarding a copper target with 100 MeV ^{22}Ne (in some cases with ^{20}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 carrier was added. From the solution the copper have been prepared in the dissoluble form of an ammoniacal complex and strontium carbonate was precipitated by means of saturated solution of natrium carbonate. The strontium carbonate was then carefully washed and was scarenged with $Fe(OH)_3$. This procedure has been verified by the previous studies on the strontium isotopes /3,4/. The radiochemically pure sources were obtained 15-20 min after stopping the irradiation.

2.2. Apparatus

Single spectra were studied with a high resolution germanium-detector spectrometer. The 13 cm^3 Ge(Li) detector of coaxial type had the energy resolution of 4 KeV for fairly high counting rates.

The γ-γ coincidence studies were carried out with the Ge(Li) detector and a 5.1 x 5.1 cm NaJ(Tl) scintillation counter. In some cases two germanium detectors were used: 13 cm^3 and 4.5 cm^3 Ge(Li) . The resolving-time of the coincidence circuit was set at 100 nsec /5/. The spectra were recorded on the 1024-KA-4020 A/12 CFK Rosendorf multichannel pulse-height analyser.

3. *Experimental results*

3.1. Single spectra

The typical gamma single spectrum is shown in Fig.1. From the studies on single spectra, taking into account the criteria of the decay with the approximately 29 min half-life and the conserving of the relative intensities, about 60 transitions were identified as belonging to the decay $^{81}Sr \rightarrow {}^{81}Rb$.

The proofs that the observed γ-rays really belong to the decay of the ^{81}Sr are the follows:

a) the chemical procedure of the source preparation;

b) for all strongest transitions the decay was followed and agrees with the approximately 29 min half-life;

c) in the reaction used to produce the ^{81}Sr activity also the activities of the neighbouring strontium isotopes were produced, i.e. in the sources from the reaction with ^{22}Ne ions the well known (from the study of Etherton et al. /6/ and from our studies/3,4/) γ-rays belonging to the decays of the ^{82}Sr and ^{83}Sr were observed, and sources produced in reaction with ^{20}Ne ions contained the activity of the ^{80}Sr known from our studies on the decay of this isotope/7/;

d) the growing-in ^{81}Rb ($T_{1/2}$ = 4.7 h) activity, as the product of the ^{81}Sr decay, was observed (known from studies of Scholz and Bakhru/8/ and also from our studies/7/).

The energies of the observed γ-transitions and their relative intensities are listed in Table 1.

The deviations of the energies of the calibration transitions from the quadratic fit were never greater than +0.2 keV. The energy determination was also controlled with known/4,6, 7,8/ γ-transitions of ^{83}Sr and ^{81}Rb. The energies of the low-intensity photons were determined using the strong transitions in ^{81}Sr as standards. The gamma-ray intensities, relative to the complex peak of 142.3; 147.8; 153.4 keV transitions were calculated using photo-efficiency curves experimentally determined for the detector. Such normalisation we chose because of the lack of any other transition in ^{81}Sr decay strong enough, which would not be disturbed by the transitions from the impurities existing in the sources. Many of the ^{81}Sr γ-transitions are very close in energy to the gammas of the ^{81}Rb and ^{83}Sr decays just complicating the analysis and especially the intensity determinations. Table 1 also contains several weak transitions (assigned with index "c") which were seen only in the coincidence spectra. Some of the high energy transitions are not seen in Fig.1, however, their existence was found in the single spectra of high energy region. The single spectrum taken with a 25 cm source to detector distance was a check for summing effects and demonstrated for example, that the 301.1 keV transition really exists in the ^{81}Sr decay. The amount of the β^+ decays was obtained from the relative intensity of the 511 keV photons. This was measured with a source placed in the vessel with aluminium walls 0.5 cm thick to assure the full annihilation of the positrons. The tails of the 511keV photons from the ^{81}Rb and ^{83}Sr decays were carefully substracted.

3.2. Coincidence studies

In order to obtain information necessary to construct essential frame of the decay scheme of the ^{81}Sr, some coincidence experiments were performed. For the purpose of picking out gamma transitions which are in a strong coincidence with others, the so-called " any $\gamma-\gamma$ coincidence" experiment was made, in which the 5.1x5.1cm NaJ(Tl) scintillation counter served as a gate detector and spectrum of the 13 cm^3 Ge(Li) detector was displayed on the 1024-channel analyser. Simultaneously two of such experiments were done, with two different gate settings: E > 120 keV and E > 550 keV. The coincidence spectra are shown in Fig.2. The energies and relative intensities of the γ-rays observed in these spectra are listed in Table II. These intensities are given relative to the intensity of the 443.0 keV transition in coincidence spectrum with the gate E>120keV.

The enhancement of some of the low energy transitions seen in part A of the Table II, is caused by coincidences with 511 keV annihilation photons. As it will be clear later, these enhanced transitions are going from the levels which are strongly fed in the positron'decay. Whereas, the diminished relative intensity of the 909keV gamma ray suggests that this is the crossover transition going from the level, which is weakly fed by the positron decay or by transitions going from higher levels. In the coincidence spectrum taken with the E> 550 keV gate the enhancement of the 153 and 188keV transitions is seen. There also appeared the 517 keV gamma ray which was covered by the strong 511 keV line in the single spectra.

The coincidence spectra with four energy regions selected from the spectrum of the NaJ(Tl) gate detector, i.e. with 175–210, 220–270, 550–630 and 650–750 keV energy regions were recorded using experimental arrangement similar to that of the "any $\gamma-\gamma$ coincidence". Additionally, in order to clarify the positions in the decay scheme of the two strongest transitions, 148 and 153 keV, the Ge(Li) – Ge(Li) coincidence experiment was performed. As the gate detector we used 4.5 cm^3 Ge(Li) and the energy selection set at 148 and 153 keV separately provided together with fast coincidences a gate for a spectrum from 13 cm^3 Ge(Li) recorded on the 512 channel analyser. The summary of this coincidence experiments is presented in Table III. The big amount of γ -rays and their close energy spacings makes the interpretation of the coincidence data difficult. It was not possible to separate the coincidences with γ -rays which energy enters the gate interval from the coincidences with a compton background and therefore in Table III there are listed all γ -rays which appear in coincidence spectrum with a given energy region.

In order to identify the states populated by positron decay and to determine, approximately, their feeding in this decay, a tripple coincidence experiment was performed. The source was placed above the 13 cm^3 Ge(Li) detector and between two 5.1x5.1 cm NaJ(Tl) scintillation counters set at an angle of 180^o. The both NaJ(Tl) counters, accepting the 511 keV annihilation photons, provided the coincidence gate. The statistic accumulated in this experiment was not sufficient enough for quantitative determination of the β^+ decay feeding the levels deexcitated by gamma rays with energies higher than 443 keV. However, the existence of the 511 keV peak in coincidence spectra with two high energy regions certificates this feeding.

The β^+ decay population of the low energy levels was estimated approximately neglecting the β^+ branching to the higher energy levels and to the ground state of ^{81}Rb .

3.3. The proposed decay scheme

A decay scheme, consistent with our data, which includes almost all strongest transitions and many of the weak ones is shown in Fig.3. The decay scheme was constructed on the basis of both the coincidence studies and energy sums, taking into account relative intensities of the transitions. The β^+ decay to high energy levels and the high energy transitions which were not placed in the decay scheme, suggest the possibility of the existence of levels laying still higher in energy, but the data were not sufficient to establish them.

A. Evidence for the 153.4, 188.3, 301.2 and 443.5 keV states

The quantitative analysis of the Ge(Li)– Ge(Li) coincidence spectra showed that the 142.3, 147.8 and 153.4 keV photons are almost in full coincidence with each other. The sum of their energies fits very well with the energy of 443.5 keV transition which was placed as the crossover transition from the 443.5 keV level.

The placement of a state at 153.4 keV was dictated by the fact that the 153.4 keV transition is the strongest one and coincides strongly with high energy transitions than the 147.8 keV transition. At this moment the placement of a state at 301.2 keV is quite natural and is confirmed also by the existence of the crossover transition to the ground state. A state at 188.3 keV with the strong transition to the ground state was placed on the basis of:

1. The relative intensity of the 188 keV gamma-ray.
2. Strong coincidences with high energy transitions.
3. The lack of the coincidence with 153.4 keV photon.
4. The observed coincidences with a 255.0 and 112.9 keV transitions which connect this state with a 443.5 and 301.2 keV states, respectively.

The placement of the 153.3, 188.3, 301.2 and 443.5 keV states is also supported by the tripple coincidence spectrum in which mainly the transitions of 142.3, 147.8, 153.4, 188.3, 255. 0, 301.2 and 443.5 keV are seen.

The quantitative analysis together with the assumptions mentioned in the previous section give the population of the states in the positron decay: about 20% of this decay is going to the 188.3 keV level, 45.4% to the 301 keV. level and 34.6% to the 443.5 keV level, the 153.4 keV level being not fed.

B. Evidence for the other states

The 574.6 keV state is placed taking into account the coincidences of the 153.4 keV photon with the 421.2 keV photon, the coincidences of the 188.3 keV photon with the 386.0 keV photon, and the adequate energy sums, which fit very well with the energy of the 574.5 keV transition. This transition was put as the crossover from this state to the ground state. A weak 132 keV peak was seen in some coincidence spectra, just suggesting the connection of the 574,6 state with the 443.5 keV state. The relative intensities of the transitions depopulating the 574.5 keV state are not balanced by the intensities of the weak transitions going to this state. Therefore this state must be populated in an immediate decay and probably in the β^+ decay. The existence of the level at 909.3 keV is strongly confirmed by coincidences of the 721.3 keV transition with the 188.3keV transition and of the 607.9 keV transition with 147.8 and 153.4 keV transitions. Here, also the intensity balance points out a quite strong feeding of the 909.3 keV level by higher γ-transitions and by betas. All other states were placed in the decay scheme mainly on the basis of energy sums, but in agreement with the coincidence data. There are the states 206.4, 812.0, 820.0, 851.0, 865.5, 1129, 1343.5, 1382, 1511 and 1553.0 keV. The transitions which are not placed in the decay scheme are assigned by the index "u" in Table 1.

4. Conclusion

It is seen from the data obtained in this study that for the full disentangling of the levels in ^{81}Rb, fed by the ^{81}Sr decay some additional experiments are necessary to be performed. The placement of some excited states should be tested by Ge(Li) – Ge(Li) coincidence experiments. The determination of the full decay energy, and the measurement of the interval conversion coefficients of the strong transitions would provide spin and parity assignements of the excited states. Some measurements of the $\gamma-\gamma$ angular correlations may also be indispensable for determining the spins. These studies are now going on and before the more complete information is gathered, the comparison with a theory is postponed.

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Table 1.

Energies and relative intensities of γ-rays from the decay of ^{81}Sr.

Energy keV	Relative photon intensity[x]	Energy keV	Relative photon intensity	Energy keV	Relative photon intensity
98±I	0.I	5II.0	I62.8	I067±I	0.2
II2.9±0.5	0.I	c 5I7±I	–	I080.7±I.0	0.4
c[xx] I3I±I	–	523.6±0.3	I.2	III0.0±I.0	0.3
I42.3±0.3	5.8	c 532±I	–	II37±I	0.3
I47.8±0.3	43.2 I00	545.2±0.5	0.2	II9I.3±I.0	0.4
I53.4±0.3	5I.2	549.2±0.5	0.6	II94.I±I.0	0.4
I72.0±0.5	0.I	560.4±I.0	0.2	I2I0.8±I.0	0.5
u[xxx] I77.6±0.5	0.I	574.6±0.3	8.7	I253±I	0.4
I88.3±0.3	29.3	u 586.2±I	0.3	I323.5±I.0	–
206.4±0.3	0.26	c 60I±I	–	I344±I	–
2I8.4±0.3	0.2	607.9±0.3	I.4	I38I±I	0.5
237.5±I.0	0.I	c 623±I	–	I399±I	0.8
245.4±0.3	I.I	632.I±0.3	0.I	u I46I±I	–
255.0±0.3	2.4	644.7±0.5	0.5	u I508±I	–
289.7±0.3	0.5	664.3±0.5	–	I553±I	–
30I.2±0.3	2.8	70I.5±I.0	2.0	u I575±2	–
u 3I4±I	0.4	7I2.I±0.5	I.8	u I600± 2	–
3I9±I	0.2	72I.3±0.3	4.I		
386.0±0.5	2.8	769±2	0.2		
387.7±0.5	2.8	u 809.0±I.0	0.4		
u4I2.6±0.5	0.2	8I9.2±I	0.I		
42I.2±0.3	2.I	85I.6±0.5	0.8		
443.5±0.3	24.2	896±2	0.3		
462.8±0.3	0.7	909.3±0.3	4.0		
465.6±0.3	I.2	922.9±0.3	0.6		
477.0±I.0	0.4	938.6±0.3	3.8		
u 486.8±0.5	2.0	978.5±0.5	0.5		
u 496.5±I.0	0.3	c I043±2	–		

x/ A 10% error in relative intensities is estimated.

xx/ Index "c" assignes lines seen in coincidence spectra only.

xxx/ Index "u" assignes transitions which are not placed in decay scheme.

Table II

Energies and relative intensities of γ-rays from the decay of ^{81}Sr observed in "any γ-γ coincidence" experiments.

A. Gated E I20 keV				B. Gated E 550 keV	
Energy keV	Relative intensity	Energy keV	Relative intensity	Energy keV	Relative intensity
98	0.7	523.6	I.8	I42.3	0.28
II2.9	0.6	574.6	7.5	I47.8	2.I6
I42.3	20.0	607.9	2.7	I53.4	6.63
I47.8	99.0	622	0.6	I88.3	I.70
I53.4	I07.0	63I	0.6	2I8.4	0.08
I88.3	34.5	658.7	2.5	245,4	0.I7
206.4	0.4	664.3	I.8	386.0	0.37
2I8.4	0.6	70I.6	2.3	443.5	0.69
237.5	0.7	7I2.I	I.6	462.8	0.I6
245.4	I.7	72I.3	6.0	465.6	0.II
255.0	4.5	8I9.2	I.4	477.0	0.2I
30I.2	2.I	909.3	2.0	486.8	0.I7
386.0	6.0	938.6	4.3	5I7.0	0.I9
387.7	6.0	978.5	I.I	523.6	0.08
42I.2	3.4			574.6	0.3I
443.5	24.2[x]				
462.8	I.6				
465.6	2.5				
477.0	I.8				
486.8	I.6				

x/ Adjusted to equal relative intensity of the 443.5 keV photon in singles:

Table III.

Coincidence summary

Gate interval in keV	γ in gate in keV	coincidence with γ in keV
I75-2I0	I72,I77,I88,206,2I8,	II3,I3I,I42,I48,I53,255,386,443,5II, 60I,608,623,632,664,72I,909,923
220-270	2I8,237,245,255,290,	I3I,I42,I48,I53,I88,2I8,237,255,443, 5II,60I,608,909
550-630	523,545,549,560,574,586, 608,623,632,644,658,664	I42,I48,I53,I88,245,30I,523,555
650-750	644,659,664,70I,7I2,72I, 769	II3,I42,I48,I53,I88,255,463,486,5I8, 574,608,7I2,769
I47.8	I47.8, I42.3	I3I,I42,I48,I53,30I,608
I53.4	I53.4	I42, I48, 42I,608, 658

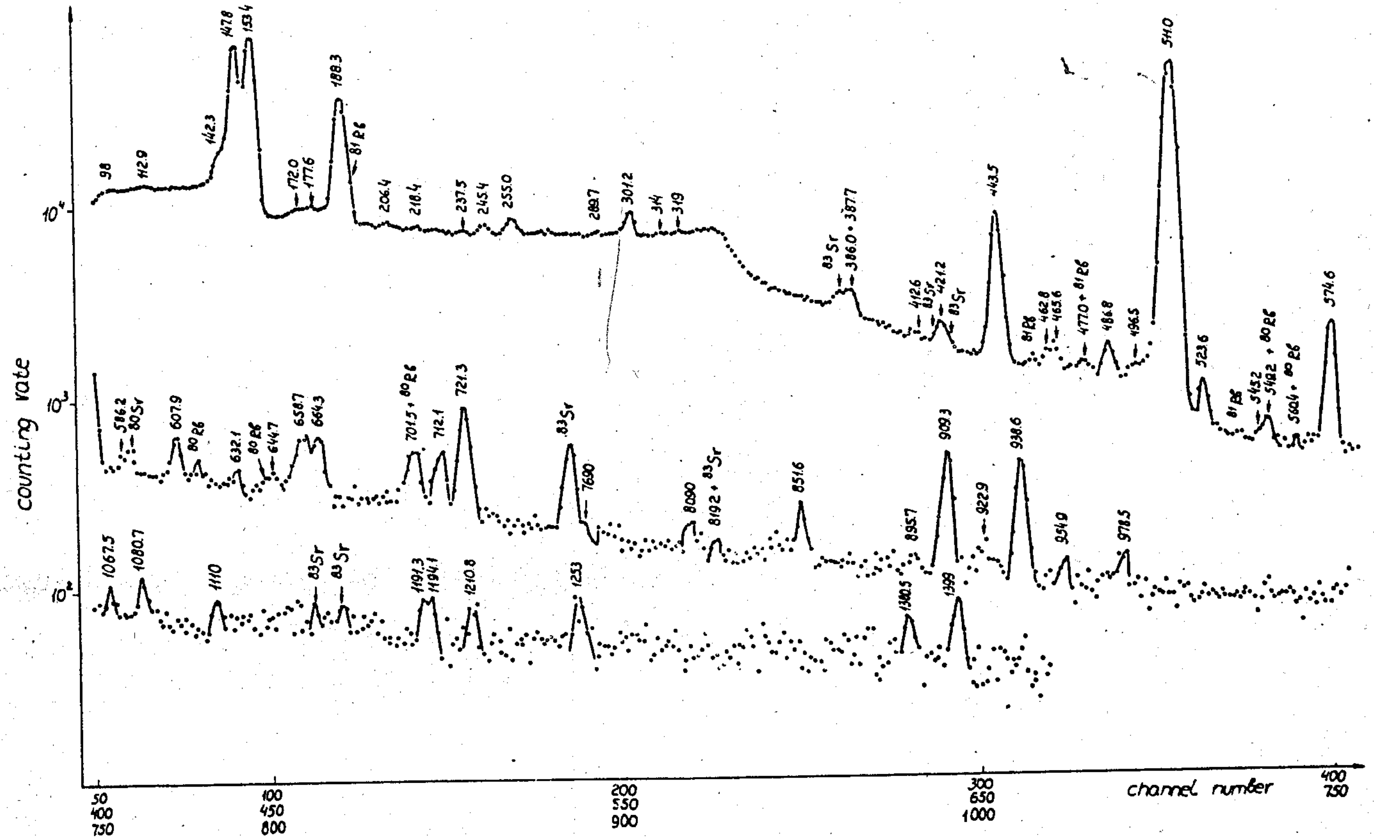

Fig.1. Gamma-ray single spectrum of ^{81}Sr taken with a 13 cm^3 Ge(Li) detector.

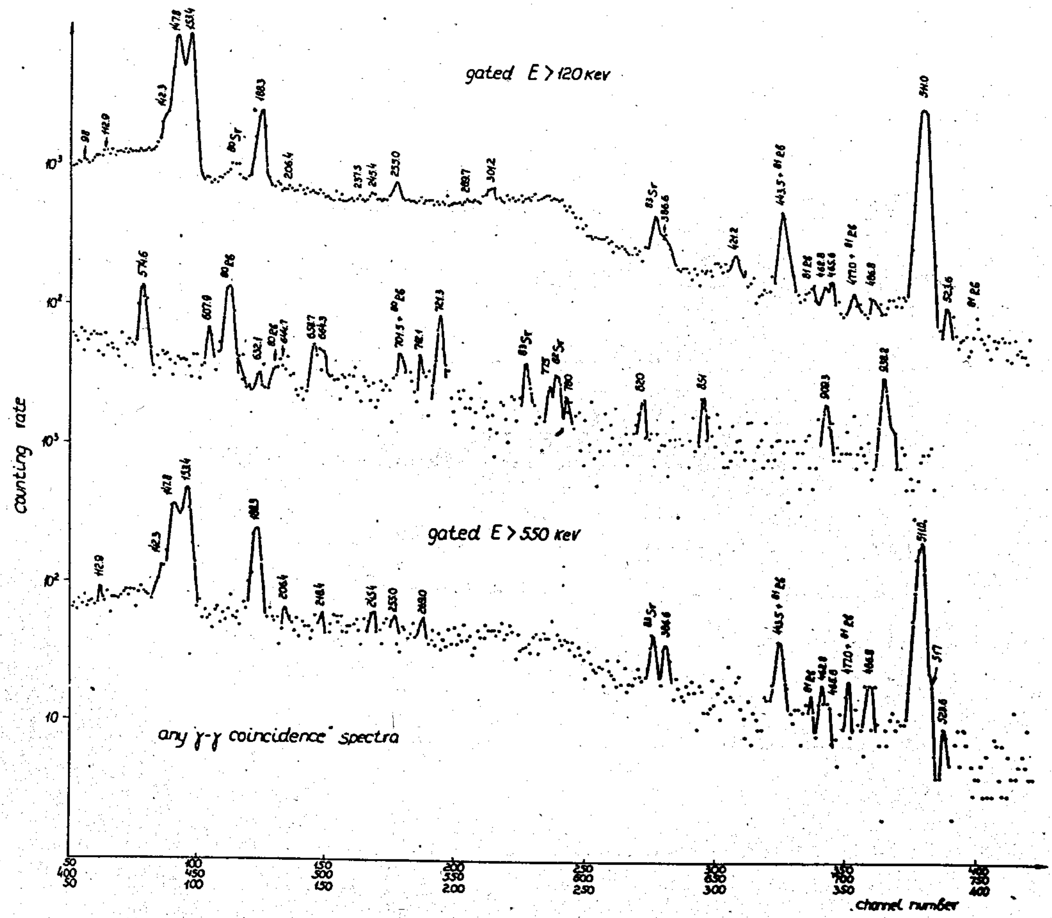

Fig.2. "Any $\gamma-\gamma$ coincidence" spectra recorded with the 13 cm^3 Ge(Li) and 5,1 x 5,1 cm NaJ(Tl).

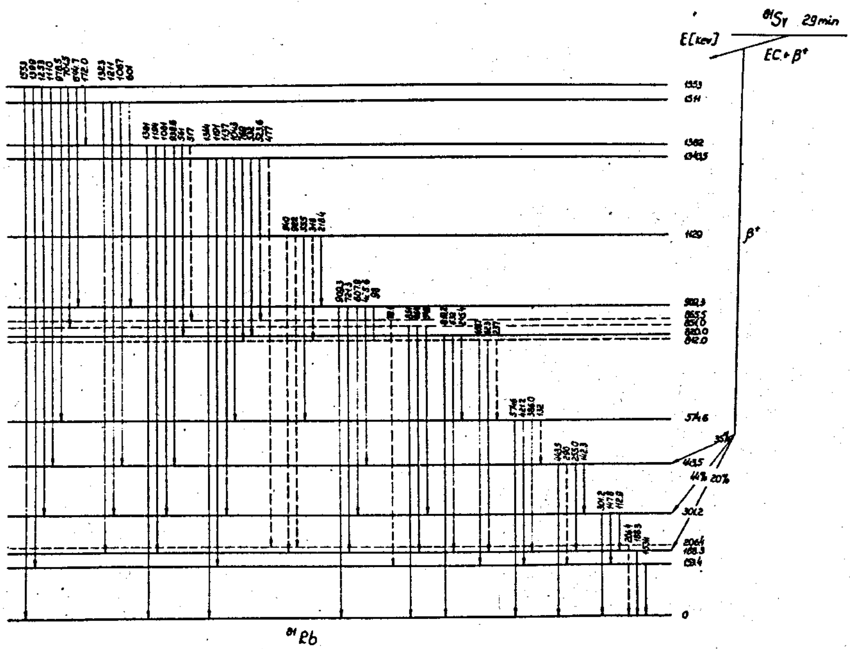

Fig.3. The proposed decay scheme for ^{81}Sr.