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THE DECAY SCHEME OF ^{127}Ba AND HALF-LIVES OF SOME LOW-LYING EXCITED STATES IN ^{123,125,127,129}Cs

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1. *Introduction*

The aim of the present study is to obtain further experimental information on the low-lying levels in $^{123-129}Cs$ excited in the beta decay of $^{123-129}Ba$. These neutron-deficient isotopes belong to the $50 < Z$, $N < 82$ region where a stable deformation has been predicted [1]. This new region of deformation has been confirmed by theoretical calculations [2,3] and by experimental data obtained from in-beam spectroscopy (even nuclei) [4-7]). The sign of this deformation is not yet well determined. The theoretical calculations in ref. [3] suggest that oblate shapes are more stable than prolate ones but the coexistence of both prolate and oblate states is also possible. Support for these predictions seems to be provided by the observation of the excited states populated in the decay of the $11/2^-$ isomeric states observed [8-10] in odd ^{127}Cs and ^{129}La isotopes. Tentative Nilsson orbital assignments for these states suggest that the $5/2^+$ first excited state in ^{127}Cs can be treated [8] as a shape isomer.

It is thus of special interest to extend our knowledge of these nuclei by studying low-spin states populated in beta decay processes. In the present paper the decay scheme of ^{127}Ba and the half-lives of some of the excited states in $^{123,125,127,129}Cs$ are reported. It is suggested that in all four cases the states connected by the E2 transitions $(5/3^+ \to 1/2^+)$ have the same deformation, and the possibility of the shape isomerism, occuring as discussed in ref. [8], is questionable. As regards the isomeric states in ^{127}Ba, marked discrepancies exist between the data reported in ref. [11] and those cited below.

Preliminary results of the present investigations have been published previously [12-16].

2. *Source Preparation*

Suspensions of 3 *g* GeO_2 in 5 *ml* 0.02 M HCl solution (size of CeO_2 grain was about 5μ) were irradiated for 20 *min* by the external 660 *MeV* proton beam of the JINR synchrocyclotron. Because of the high recoil energy, 20-40% of the spallation reaction products are stabilized in the liquid phase and can be easily separated from the target material by filtration by analogy with the Ta_2O_5 suspension technique as described in ref. /17/. After filtration the filtrate was stired during 60 *sec* with about 10 *mg* cation exchange resin (Dowex 50 x 5, resin size 20μ or Aminex A5). The rare earths (Pr, Ce and La), Ba and partially Cs were adsorbed on the resin, which was transformed into the NH_4^+-form. The rare earths including a few times 100 *mg* of a Ce carrier from the target material were eluted with 0.8 alpha-hydroxy-isobutyric-acid (alpha- HIB). In order to elute a narrow Ba - peak it was necessary to transform the NH_4^+ -cation exchanger into the NH_4^+ -form by washing the column with 1M HC*l*. Under these conditions Cs was eluted. Using 6M NHO_3 a very narrow peak of pure Ba was washed from the column (fig. 1). To transform the nitrates into the oxides the Ba fraction (1-2 drops 6M HNO_3) was evaporated until dryness on a 5 x 5 mm^2 Ta foil and then heated to about 800 K. The Ba-isotope separation was carried out at the YASNAPP-facility /18/ using the pipe type surface ionization ion source /19/. The activity of the ^{127}Ba samples (measured usually 20 *min* after the end of irradiation) was of the order of 0.5 *m*Ci. To investigate also the ^{123}Ba and ^{125}Ba isotopes, the samples of the Ba fraction were prepared during about 1 *min* from a 100 *mg* La target in HNO_3 solution, irradiated for 20 *sec*. The Ba isotopes were collected as $BaSO_4$ by carrier precipitation.

Samples were also prepared by the method of fast extraction of isobars by direct electromagnetic mass-separation from proton irradiated tantalum targets /20/.

3. *Singles Gamma-Ray Spectra Measurements of* ^{127}Ba

The singles gamma-ray spectra (*figs. 2* and *3*) of ^{127}Ba (mass-separated sources) were measured using 2,4 *cc* and 41 *cc* Ge(Li) detectors with system resolutions of 0.7 *keV* at 122 *keV* and 2.4 *keV* at 1332 *keV*, respectively. The energies of the gamma-rays were determined by taking combination spectra of ^{127}Ba, ^{133}Ba and ^{126}Ba sources. The results obtained from a few series of measurements are given in *table 1*. These results should be compared with the data of ref. /11/ where two isomeric states in ^{127}Ba with half-lives of (10 ±1) and (18±1) *min* were reported. The value of 10 *min* can be in agreement (in two standard error limits) with the half-life adopted here (see insert in *fig. 2*). The 18 *min* activity (in the 10-2500 *keV* gamma energy region) in this experiment was not observed.

4. *Conversion-Electron Spectra Measurements of* ^{127}Ba

The measurements of the conversion-electron spectra (*fig. 4*) were carried out using a Si(Li) detector (1.6 *cm* x x 0.3 *cm*) with a 2.5 *keV* energy resolution at 100 *keV*. To check the purity of the sources simultaneously with the conversion electron measurements the gamma-ray spectra were recorded with a 38 *cc* Ge(Li)-detector. The final results obtained from three series of measurements are given in *table 2*.

5. *Gamma-Gamma Coincidence Measurements of* ^{127}Ba

The gamma-gamma coincidence measurements were carried out using 41 and 45 *cc* Ge(Li) detectors with energy resolutions of 2.4 and 2.9 *keV*, respectively, for the 1332 *keV* γ-ray of ^{60}Co. The detectors were oriented at 90°. Pulses from the coincidence system /22/ (50 *ns* resolving time) were used to open the gates of two 4096-channel ADC units connected to an HP 2116C computer. The coincidence spectra obtained with the gates set on the more intense photopeaks are shown in *fig. 5*.

Table 1

Gamma-rays observed in the decay of ^{127}Ba

E_γ	I_γ	E_γ	I_γ
KX	470 ± 50	1385.2 ± 0.5	0.8 ± 0.2
66.3 ± 0.3	17.1 ± 1.7	1437.5 ± 1.0	~ 0.1
72.8 ± 0,5	6.1 ± 0.5	1448.8 ± 0.5	0.4 ± 0.1
114.8 ± 0.3	74.7 ± 3	1500.1 ± 0.3	3.0 ± 0.3
139.0 ± 0.8	0.8 ± 0.4	1511.2 ± 1.0	1.0 ± 0.1
180.8 ± 0.3	100	1522.0 ± 0.7	0.6 ± 0.1
429.3 ± 0.6	2.2 ± 0.4	1566.0 ± 0.3	3.1 ± 0.3
441.0 ± 1.0	0.4 ± 0.2	1576.3 ± 1.0	0.5 ± 0.1
451.5 ± 1.0	0.7 ± 0.2	1618.0 ± 0.3	2.0 ± 0.3
511.0	877 ± 70	1697.0 ± 0.8	0.4 ± 0.2
523.5 ± 0.7	3.5 ± 0.8	1753.6 ± 0.3	2.0 ± 0.3
532.1 ± 0.7	0.4 ± 0.1	1800.1 ± 0.6	0.6 ± 0.2
567.5 ± 0.3	2.8 ± 0.3	1842.2 ± 0.6	0.9 ± 0,2
573.9 ± 0.5	0.7 ± 0.2	1915.3 ± 0.6	0.9 ± 0.3
578.0 ± 0.3	5.2 ± 0.5	1920.6 ± 0.8	0.3 ± 0.1
619.0 ± 1.0	~ 0.1	1950.8 ± 0.6	1.1 ± 0.2
621.5 ± 0.8	0.2 ± 0.1	1962.8 ± 0.8	0.5 ± 0.1
625.5 ± 0.7	0.4 ± 0.1	1981.8 ± 0.3	1.8 ± 0.2
647.1 ± 0.8	0.4 ± 0.1	1991.9 ± 0.6	1.0 ± 0.1
691.9 ± 0.7	0.4 ± 0.1	2028.2 ± 0.7	0.5 ± 0.1
713.5 ± 0.8	~ 0.1	2057.0 ± 0.6	1.0 ± 0.2
872.5 ± 0.5	0.8 ± 0.1	2075.0 ± 0.6	0.9 ± 0.2
1012.3 ± 0.5	0.9 ± 0.1	2089.8 ± 0.4	1.3 ± 0.2
1019.8 ± 0.5	1.3 ± 0.1	2100.3 ± 0.5	1.1 ± 0.2
1062.0 ± 1.0	0.4 ± 0.1	2141.0 ± 0.8	0.3 ± 0.1
1084.9 ± 0.5	3.5 ± 0.3	2172.0 ± 0.6	1.1 ± 0.2
1108.3 ± 0.5	0.9 ± 0.2	2182.0 ± 0.3	1.8 ± 0.2
1135.2 ± 1.0	~ 0.1	2189.0 ± 0.7	0.3 ± 0.1
1150.7 ± 0.7	1.5 ± 0.2	2222.4 ± 0.7	0.5 ± 0.1
1201.0 ± 0.3	13.0 ± 1.5	2238.0 ± 1.0	0.4 ± 0.1
1222.9 ± 0.8	0.2 ± 0.1	2321.2 ± 0.5	1.2 ± 0.2
1289.3 ± 0.4	1.0 ± 0.1	2467.8 ± 0.7	1.2 ± 0.2

Table 2

Conversion coefficients of low energy γ-transitions in the decay of ^{127}Ba

E_γ (keV)	Internal conversion coefficients: experimental[a]		theoretical/21/: M1		theoretical/21/: E2		Assigned multipol.
	α_K	α_L	α_K	α_L	α_K	α_L	
72.8		~0.3		0.26		2.2	(M1)
114.8	0.5±0.1	0.09±0.02	0.54	0.07	0.78	0.29	M1+E2
180.8	0.14±0.03	0.04±0.01	0.15	0.02	0.18	0.04	E2+M1

a) The experimental conversion coefficients were normalized to the α_L value of the 66.3 keV E2 transition.

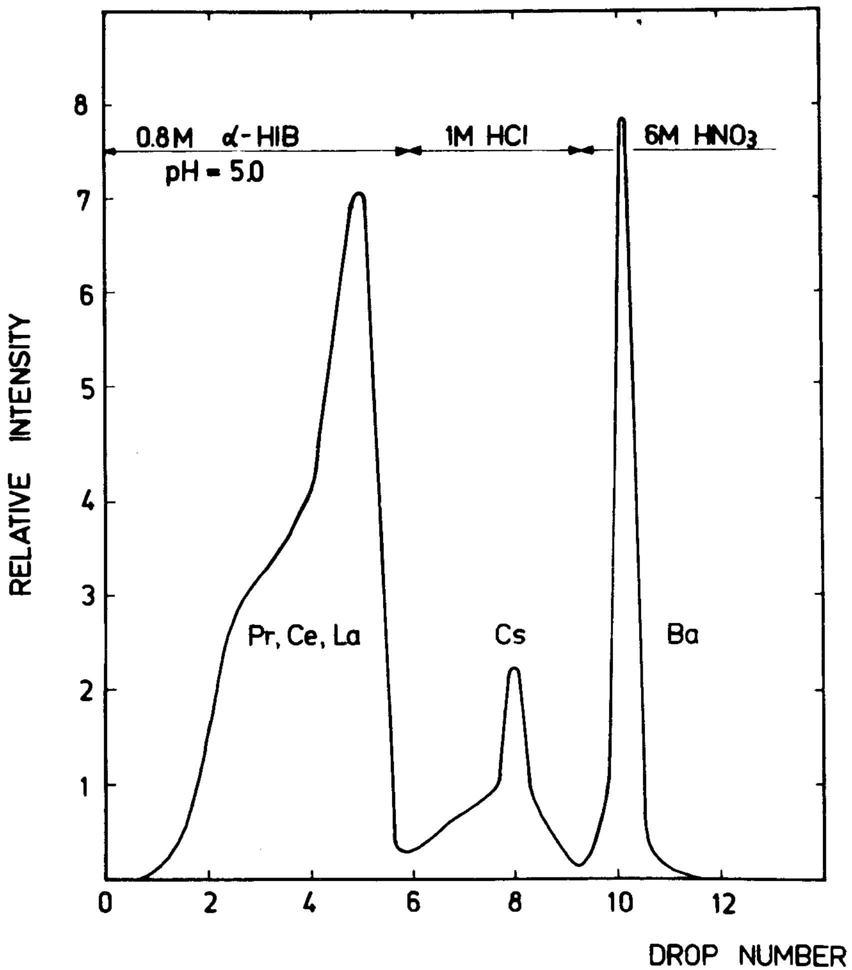

Fig. 1. Radio-chromatogram of the Ba *-separation from the spallation products* (RE *and* Cs) *of a 660 MeV proton irradiated* CeO_2 *target. Micro-cation exchange-column (Aminex A5; 2x15 mm).*

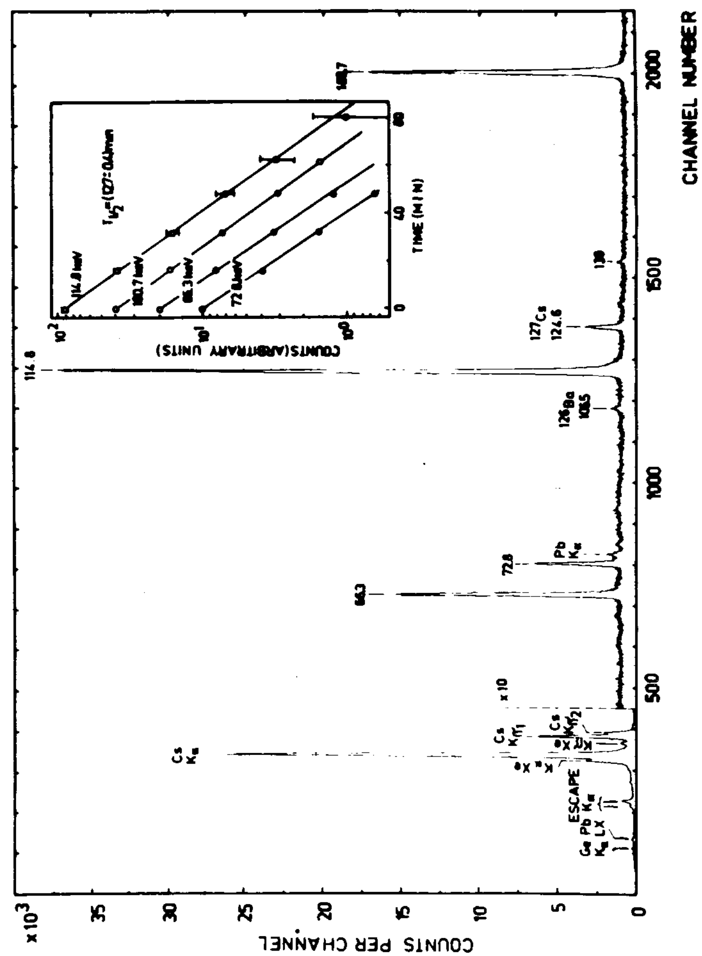

Fig. 2. Low energy part of γ*-radiation from mass-separated* ^{127}Ba *sources observed with a 2.4 cc* Ge(Li) *-detector. Decay curves of the most intense* γ *-lines are shown in the insert.*

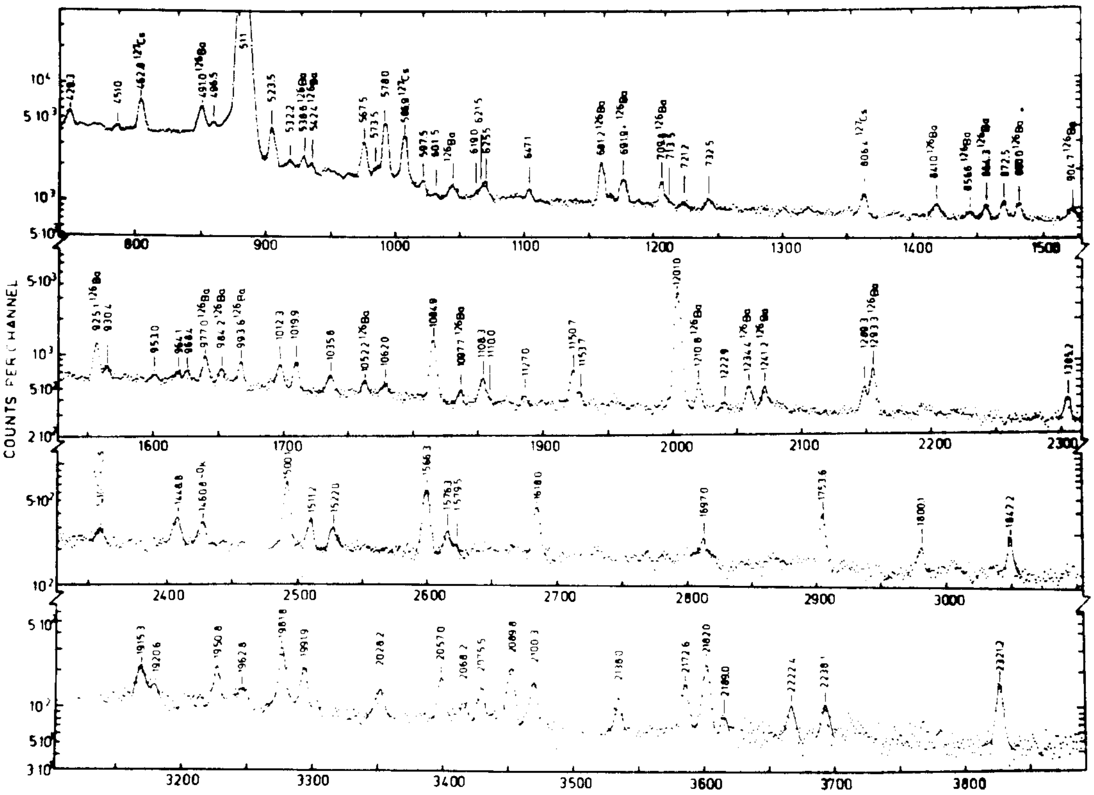

Fig. 3. High energy part of the single γ-ray spectrum of ^{127}Ba observed with a 41 cc Ge(Li) detector.

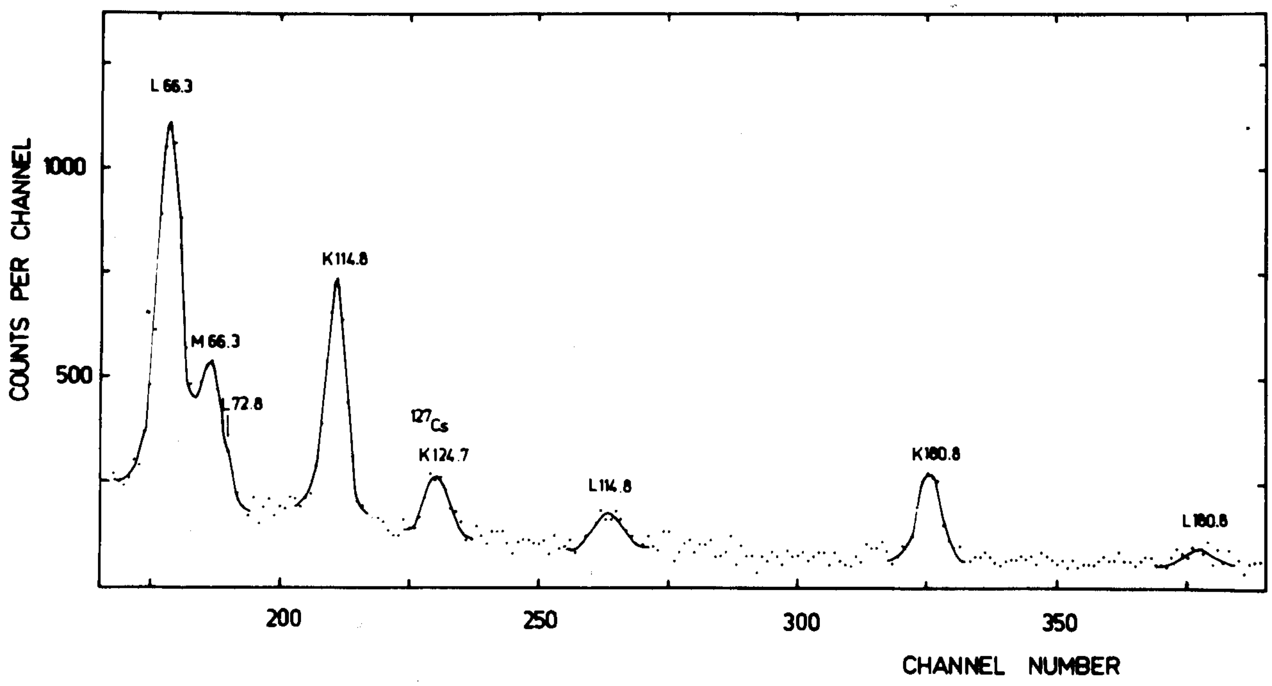

Fig. 4. Conversion-electron spectrum of ^{127}Ba observed with a 1.6 cm ϕ x 0.3 cm Si(Li) detector.

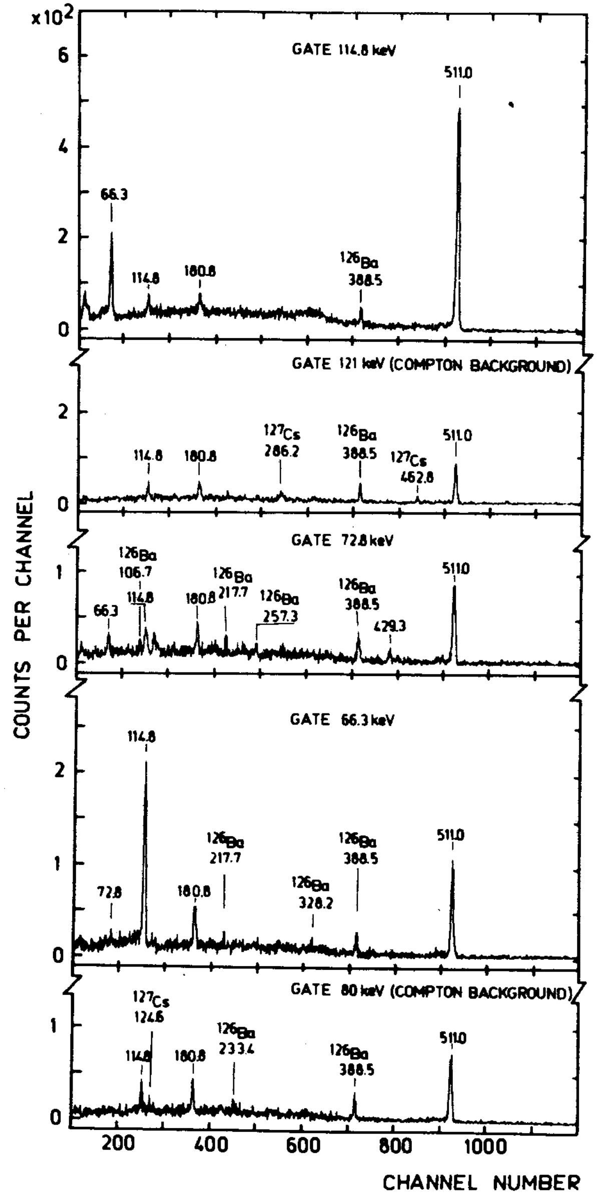

Fig. 5. Gamma-ray spectra in coincidence with the 66.3, 72.8 and 114.8 keV transitions. Gamma-spectra coincident with the Compton background are shown for comparison.

6. Beta-Gamma Coincidence Measurements of ^{127}Ba

The beta-gamma coincidence measurements were carried out using 35 *cc* Ge(Li) and NaI(Tl) detectors as the gating crystals and a 1 cm^2 x 1.5 *cm* Si(Li) detector with a resolution of 8 *keV* for the 975 *keV* conversion electron line of ^{207}Bi to obtain the coincidence beta-spectra. The detectors oriented at 180° were coupled to the same coincidence system used for the gamma-gamma coincidence measurements (sect. 5). The continuous beta-spectra distorted by the back-scattering and summing effects in the crystal were corrected using the method described in ref. /23/ . As standard sources ^{138}Pr and ^{140}Pr with well known end point energies /24,25/ were applied. As an example, the beta-spectrum obtained in coincidence with the 180.8 *keV* gamma-ray is shown in *fig. 6*.

The β^+-ray spectra obtained in coincidence with the more intense gamma-lines were consistent and yielded the maximum energy for the beta-decay of 3.45 ± 0.10 *MeV*, which is in good agreement with the semi-empirical mass formula given in ref. /26/ . Special attempts to reveal the β^+ component associated with the isomeric state /11/ have not been successful. This result together with the data of sect. 3 indicates that the 10 and 16 *min* activities reported in ref. /11/ in this experiment have not been observed.

7. Half-Life Measurements of Low-Lying Excited States in ^{123,125,127,129}Cs

The half-lives of low-lying excited states in $^{123-127}$Cs isotopes were measured using a NE 102 (3.4 *cm* ϕ x x 1.5 *cm*) plastic scintillator (mounted on a FEU-36 photomultiplier tube) as the start detector and a 27 *cc* Ge(Li) detector to obtain the delayed coincidence gamma-spectra. These spectra were measured using a slightly modified (one of the ADC units was fed by the output signals from a time-to-pulse-height convertor) two para-

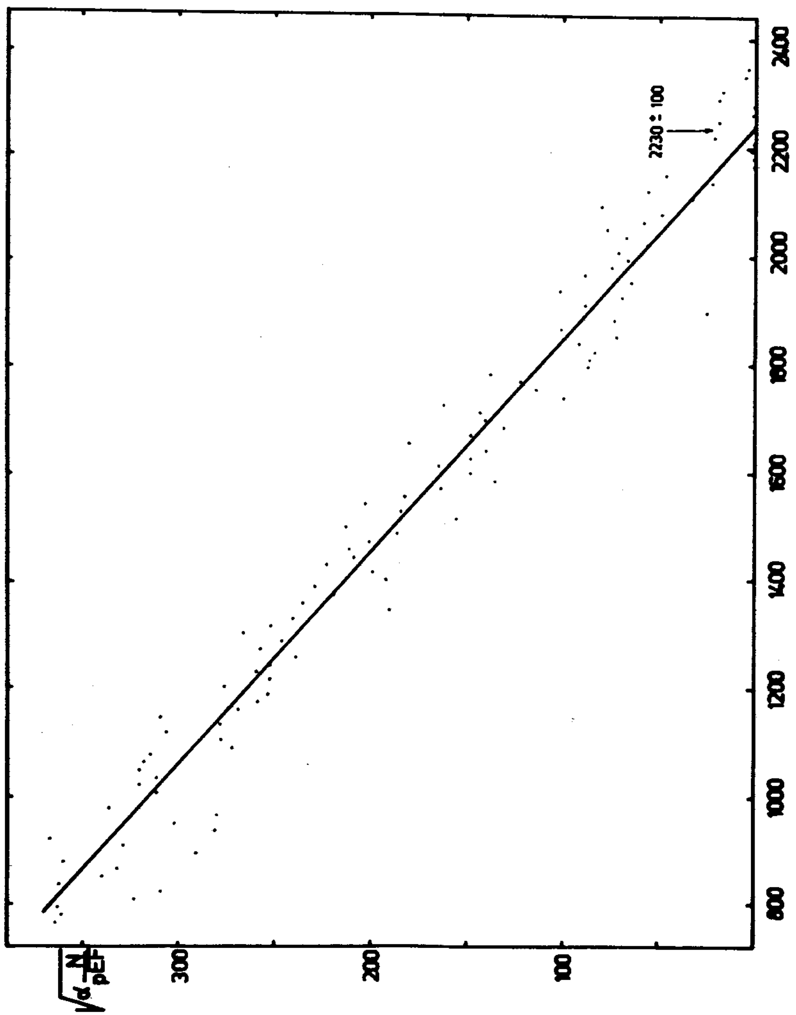

Fig. 6. Fermi-Kurie plot of the β^+ *spectrum obtained in coincidence with the 180.8 keV* γ*-ray of* ^{127}Ba.

meter analysis equipment used earlier in the $\gamma-\gamma$ experiments (sect. 5). The time resolution of the coincidence circuit was 8 *ns* FWHM with a gate set at 100 *keV* in the stop detector.The results of the $\beta-\gamma$ coincidence experiments are shown in *fig. 7*.

In the case of ^{129}Cs a NE102(1 *cm* ϕ x 0.1 *cm)* plastic scintillator (mounted on a EMI9524S photomultiplier tube) was used as a stop detector and the 27 *cc* Ge(Li) detector as a start one. The ^{129}Ba sources used in this experiment were prepared by implantation of the barium ions into the scintillator material in the electromagnetic mass-separator. The prompt and delayed γ-ray spectra gated by the 6.54M + N ... conversion electron line and LX radiation recorded in the plastic scintillator are shown in *fig. 8*.

The final results of these two experiments are given in *table 3*.

8. The Decay Scheme of ^{127}Ba

In the $\beta-\gamma$ coincidence experiment only one gamma transition of 66.3 *keV* was observed in the delayed coincidence gamma-ray spectra (*fig. 7*). This implies the existence of an excited state of the same energy. Furthermore, the $\gamma-\gamma$ coincidence measurements (*fig. 5*) clearly indicate that the 66.3 *keV* transition is in coincidence with the γ-rays of 72.8 and 114.8 *keV*. Since the 114.8 *keV* γ-transition is not observed in coincidence with the 72.8 *keV* one, it follows that there are two levels at 139.0 and 181.0 *keV*. These levels are supported by the cross-over transition of 139.0 and 180.8 *keV* observed in the single gamma-ray spectra. The three well established levels at 66.3, 139.1 and 181.0 *keV* served as a main basis for the further construction of the decay scheme shown in *fig. 9*.

The spin and parity of the gound state of ^{127}Cs has been found /31-33/ to be $1/2^+$. By using the intensity balance of gamma transitions depopulating the $11/2^-$ isomeric state in ^{127}Cs the spins and parities of the first and second excited states were estimated in ref. /8/ to be

Table 3
Half-lives of some excited states in odd Cs isotopes

Isotope	^{123}Cs	^{125}Cs	^{127}Cs	^{129}Cs
E_γ(keV)	94.5	85.4	66.3	6.54
$T_{1/2}$ (ns)	9 ± 3	14.5 ± 1.5	24.5 ± 3	72 ± 6

a) Mean value obtained from coincidence measurements (fig.8) between 6.54M + ... electrons + LX-radiation and the 129.1, 182.3, 202.3 and 214.3 keV γ-rays (the most intense γ-transitions populating the 6.54 keV first excited state in ^{129}Cs).

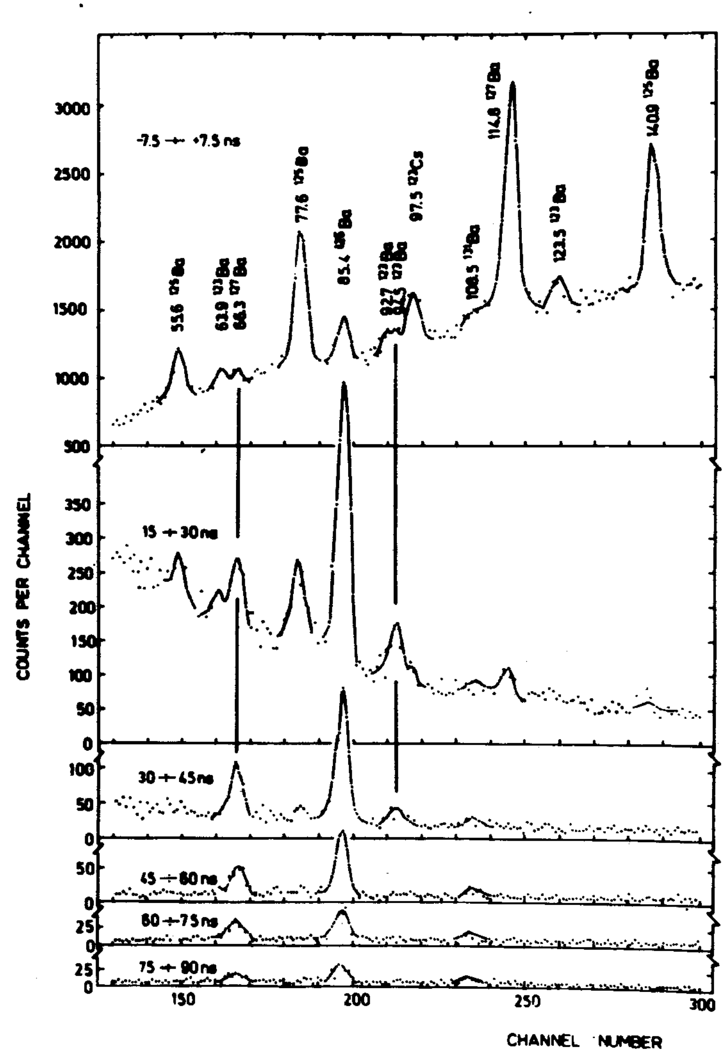

Fig. 7. Prompt and delayed coincidence γ-ray spectra (obtained by adding the counts of 26 measurements) of the short lived Ba *fraction gated by β^+ radiation recorded in the plastic scintillator with an integral gate set above 500 keV.*

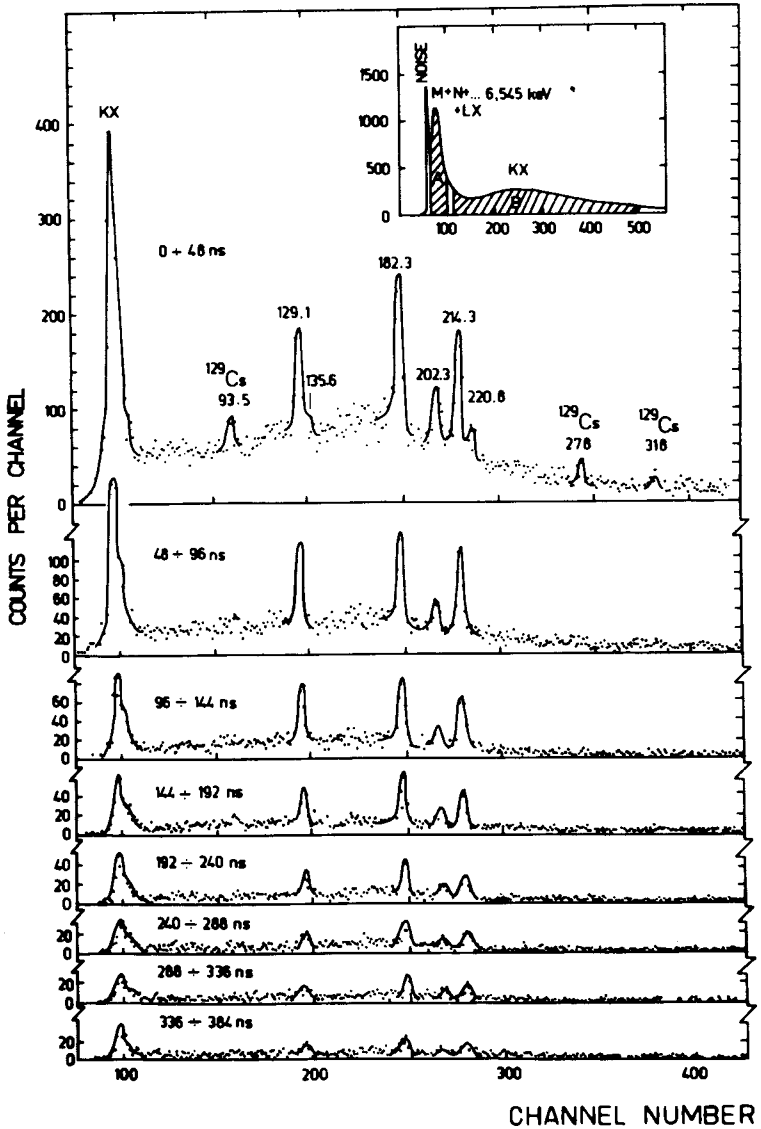

Fig. 8. Prompt and delayed coincidence γ-ray spectra of ^{129}Ba obtained with a gating window (A) set on the 6.54 keV M+N... conversion electron line and LX-radiation. In the γ-ray spectra gated by KX radiation (window B) no γ-lines were observed in the delayed spectra.

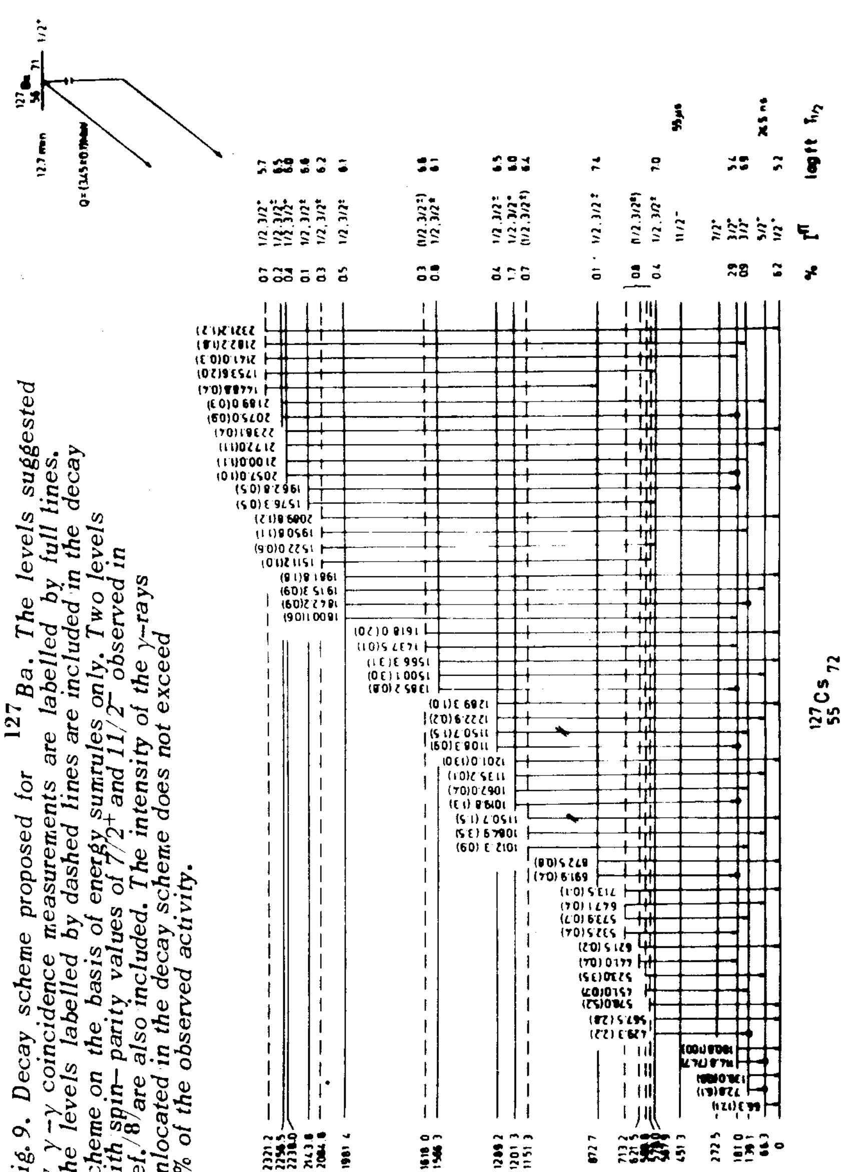

Fig. 9. Decay scheme proposed for ^{127}Ba. The levels suggested by γ-γ coincidence measurements are labelled by full lines. The levels labelled by dashed lines are included in the decay scheme on the basis of energy sumrules only. Two levels with spin-parity values of $7/2^+$ and $11/2^-$ observed in ref./8/ are also included. The intensity of the γ-rays unlocated in the decay scheme does not exceed 1% of the observed activity.

$5/2^+$ and $3/2^+_1$ respectively. These values are compatible with our experimental data.

The high intensity of the beta component to the ground state (log ft = 5.2) and no population (in experimental error limits) of the 66.3 *keV* $5/2^+$ state in the beta decay made it possible to conclude that the ground state spin value of ^{127}Ba is $1/2^+$. Taking into account the beta branch (log ft = 5.4) to the 181 *keV* level and the multipolarities of the 114.7 and 180.8 *keV* gamma transitions (*table 2*) the spin and parity of this state are likely to be $3/2^+$. The 1/2 or 3/2 spin values for higher levels have been postulated on the basis of the systematics /34/ of the log ft values in the neighbouring nuclei.

9. Discussion

Figure 10 shows the systematics of some low-lying levels of odd-mass Cs isotopes /27-30/ relative to the lowest $5/2^+$ state. As it is seen from this figure the first $1/2^+$ state is systematically lowered with decreasing mass number A, and starting from A = 129 it becomes the ground state of the lighter Cs isotopes. The same tendency can be observed for the low-lying $3/2^+$ states. The general trend mentioned above leads to a level sequence in the light Cs isotopes the properties of which cannot be described by the single particle shell model. To explain the experimental data of the ground state of ^{125}Cs and ^{127}Cs in the framework of the intermediate coupling version of the unified model /35,36/ adjustable parameters indicating deformable cores have to be used. This seems to suggest that the studied nuclei should be treated as deformed ones in agreement with the theoretical calculations of refs. /2,3/.

In the decay of ^{127}Ba the two strong allowed β^+-transitions to the ground and third excited states are observed (*fig. 9*). Assuming that these two levels belong to the same rotational band with K = 1/2 the theoretical ratio /37/ of ft-values for these transitions was estimated (about 2) to be in agreement with the experimental one. An ana-

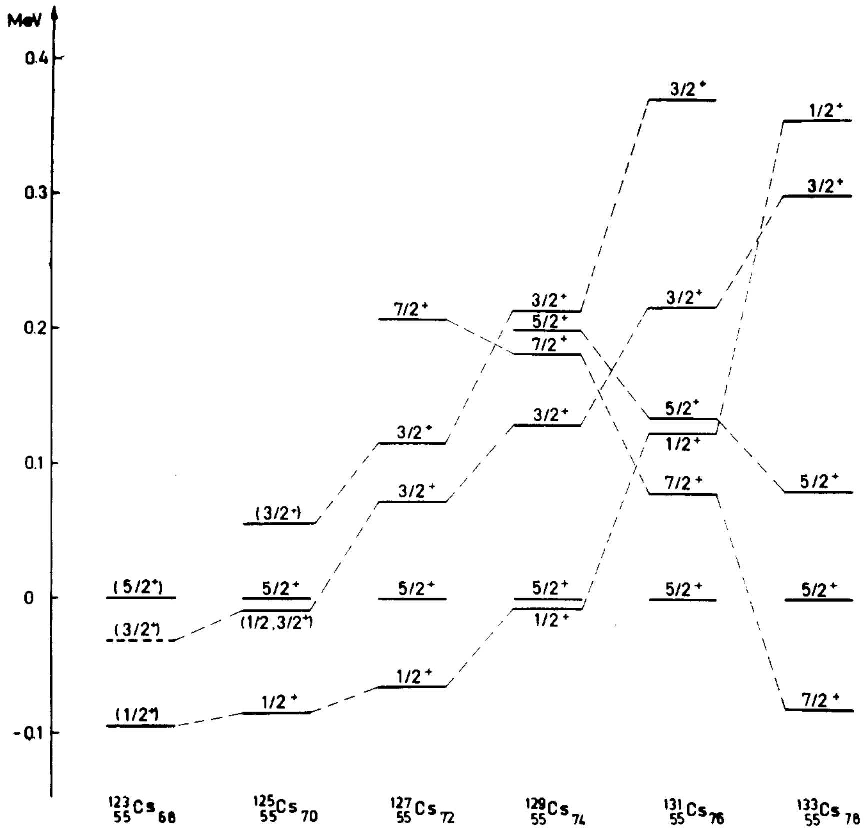

Fig. 10. Systemstics of the low-lying levels of odd-mass Cs *isotopes /27-30/ relative to the first $5/2^+$ states.*

lysis of the level energy, intensity and B(E2) transition probability (*table 4*) led the authors to the conclusion that the 66.3 *keV* $5/2^+$ state cannot be treated as a further member of the rotational family of interest. Thus, a rotational nature can be assigned only to the 181 *keV* $3/2^+$ state. This conclusion seems to be supported by the small amount of M1 radiation in the 181 *keV* gamma-transition (*table 2*) and the energy consistency with the first 2^+ excited state in the equivalent even-even nucleus ^{126}Xe /38/ (assuming the decoupling parameter to be small).

According to the quasi-particle Nilsson model /3/ the $1/2^+$ [420] orbit (for $\delta > 0$) can be assigned to the unpaired proton of the lighter Cs isotopes. To explain the nature of the $11/2^-$ isomeric state in ^{127}Cs, it has been suggested /8/ that this state and two others ($7/2^+$ at 272.5 *keV* and $5/2^+$ at 66.3 *keV*) via which the isomeric level is depopulated by gamma-transitions, should be described by the Nilsson orbitals $11/2^-$ [505], $7/2^+$ [413] and $5/2^+$ [413] for the oblate shape. Hence, the $5/2^+$ first excited level would be a candidate of the intriguing shape isomerism. According to the theoretical calculations /3/ and the systematics given in *fig. 10* one could expect that the $5/2^+$ states in the neighbouring odd Cs nuclei should reveal similar properties. The experimental B(E2) values confirmed the same nature of these levels but instead of the expected retardation an enhancement has been observed (*table 4*). Furthermore, according to the data of refs. /8,9/ the 385.5 *keV* E3 transition, connecting the $11/2^-$ and $5/2^+$ states in ^{127}Cs, has the theoretical single particle speed. These facts seem to indicate that the ground and all excited states (including the $11/2^-$ level) in ^{127}Cs observed in ref. /8/ have the same sign of deformation.

To summarize, the experimental data obtained in the present work did not reveal any consistency with the shape isomerism predictions /3/. The same deformation sign is to be assigned to ^{127}Cs and to the ground state of ^{127}Ba. The ground state of ^{127}Cs can be better described by the prolate shape of the nucleus than by the oblate one. The high energy part of the excited states observed in

Table 4

Reduced E2 transition probabilities for odd Cs isotopes calculated on the basis of the data given in table 3.

Isotope	Transition	E_γ(keV)	B(E2) exp ($e^2 \times 10^{-48} cm^4$)	B(E2) exp / B(E2) s.p.
^{123}Cs	$(5/2^+) \to (1/2^+)$	94.5	0.25 ± 0.08	21.5 ± 7.2
^{125}Cs	$5/2^+ \to 1/2^+$	85.4	0.20 ± 0.02	17.1 ± 1.8
^{127}Cs	$5/2^+ \to 1/2^+$	66.3	0.18 ± 0.02	15.9 ± 1.9
^{129}Cs	$5/2^+ \to 1/2^+$	6.54	0.16 ± 0.02	13.4 ± 1.2
^{131}Cs	$1/2^+ \to 5/2^+$	123.7	0.30 ± 0.01 a)	8.2 ± 0.2

a) Ref. /41/.

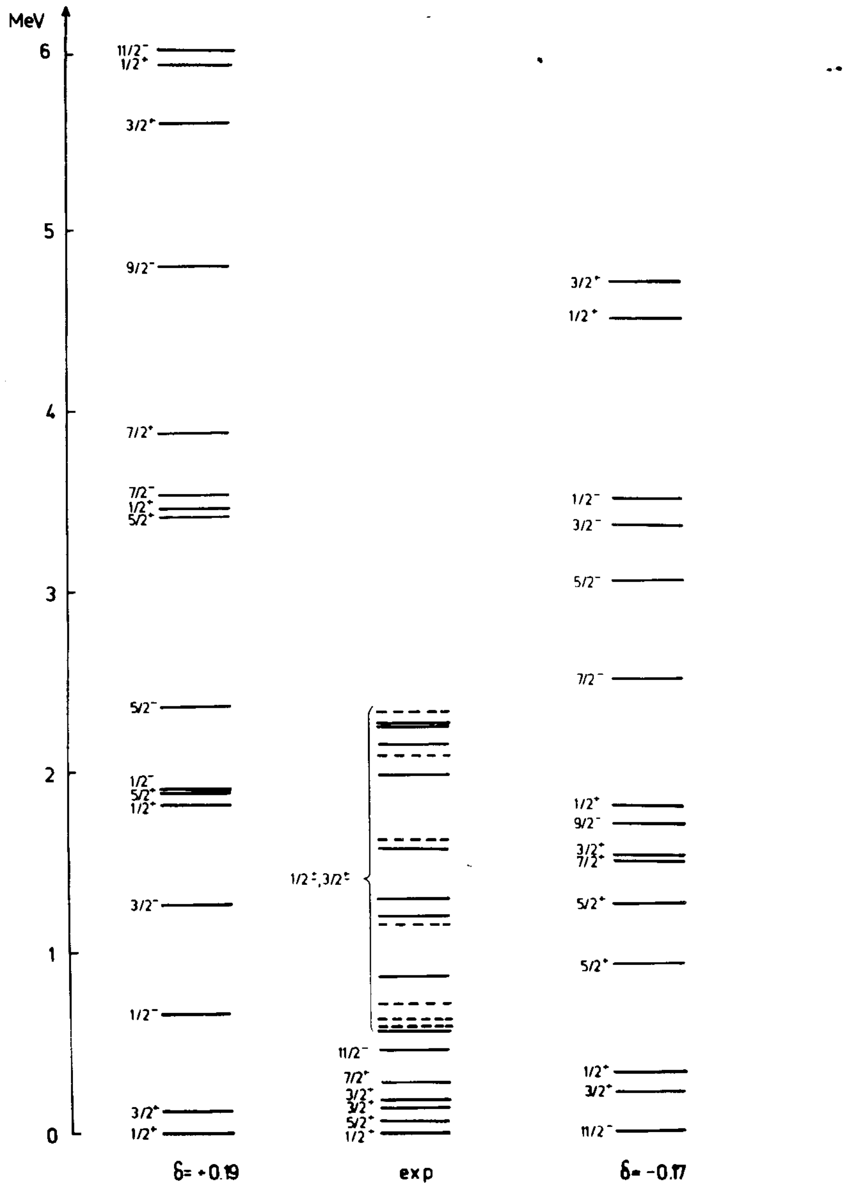

Fig. 11. Comparison of the experiment and theoretical intrinsic levels calculated [39] *using the Saxon-Woods potential for equilibrium deformation of* ^{127}Cs.

^{127}Cs cannot, however, be explained in the framework of the simple Nilsson model because the number of 1/2, 3/2 states observed in the experiment exceeds the number of expected ones, as can be seen in *fig. 11* where the intrinsic states in ^{127}Cs calculated with Saxon-Woods potential [39] are compared with the experiment.

It is worth noting that the unified model in the intermediate coupling version [35,36] and the pairing + quadrupole forces model [40] are also able to explain the experimental data of the ground states of odd Cs isotopes. The energy systematics of the low-lying levels shown in *fig. 10* seems to continue the general trend of those given in ref. [40] for heavier Cs nuclei.

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Note added in proof: During the course of publication of the present paper, a new work on the ^{127}Ba decay has been published by Pathak and Preiss (Phys. Rev., C11, 1762 (1975)). Their results are in agreement with the data presented here.

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