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# A NEW ISOMERIC STATE IN $^{134}$Pr AND EXCITED STATES OF $^{134}$Ce

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# A NEW ISOMERIC STATE IN $^{134}$Pr AND EXCITED STATES OF $^{134}$Ce

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## 1. Introduction

A few works[1-4] have been devoted to the excited states of $^{134}Ce$ , one of the nuclei at the edge of the expected region of deformation[5]. Three of these[3,4] have been performed on the ($HI$ , $xn$ ) and ( $\alpha$ , $xn$ ) reactions, where the ground-state quasi-rotational band was revealed. The subject of the present work was to obtain further information on the low lying levels excited in the beta decay of $^{134}Pr$ . In our studies of the excited states of $^{134}Ce$ populated in the decay of $^{134}Pr$ we encountered difficulty in estimation of the relative intensity of gamma transitions observed in single spectra. It turned out that there is a group of gamma-rays the relative intensity of which depends on the source history. A more careful analysis of the spectra obtained from $^{134}Pr$ and $^{134}Pr$ in equilibrium with $^{134}Nd$ indicates the existence of an isomeric state in $^{134}Pr$ .

## 2. Source Preparation

The sources used in this experiment were obtained by spallation reaction from a $(NH_4)_2[Gd\ DTPA]\cdot H_2O$ x/ target irradiated with 660 MeV protons on the external beam of the JINR synchrocyclotron. The radioactive elements produced in this reaction were separated from the target material by sorption on the cation exchange resin Dowex 50 x 8 as discribed in ref. /6/ and according to their atomic number $Z$ by the cation exchange chromatographic method. A 0.5 M buffer solution of ammonium alpha-hydroxy-isobutyrate was used as an eluent. Then the $^{134}Pr$ and $^{134}Nd$ source were prepared by electromagnetic isotope separation of the praseodymium and neodymium fractions using a surface ionization ion source /7/. The admixture of the neighbouring isotopes in the sources were estimated to be negligibly small from the single gamma-ray spectra.

## 3. Single Gamma-Ray Spectra

The single gamma-ray spectra were studied with a 38.5 cc Ge(Li) detector with a resolution of 3.7 keV at 1333 keV. The gamma-ray energies of the larger peaks were determined by counting the spectra simultaneously with several well known standards ( $^{60}Co$, $^{54}Mn$, $^{88}Y$, $^{133}Ba$, $^{169}Yb$, $^{207}Bi$ ) using a computer coupled system of

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x/ *DTPA* - Diethylentriaminpentaacetate.

data handling[8]. These peaks, in turn, were used to determine the energies of the weaker peaks in spectra taken without the standard sources. The experimental measurements, usually, were started 25-30 min after the end of the irradiation. In order to obtain the decrease of the intensities of the gamma-lines, a few spectra from each source, for a 10-15 min period of accumulation were recorded in succession. Measurements were carried out with two different $^{134}Pr$ sources. Figure 1 shows typical gamma-ray spectra observed with the Ge(Li) detector. The upper (A) spectrum was obtained in an experiment on mass-separated sources of the praseodymium fraction. The lower one (B) corresponds to the sources prepared by mass-separation of the neodymium fraction in equilibrium with $^{134}Pr$ daughter. Gamma transitions corresponding to $^{134}Nd$ isotope are labeled by crosses. Because of an admixture of the praseodymium in the neodymium fraction ($\leq 15\%$) these spectra cannot be compared in detail. However, a comparison of the two spectra shows that the 184.3, 188.9, 667.2, 1125.4 and 1196.8 keV gamma transitions are greatly reduced in the spectrum (B) relative to the (A) one. A more careful analysis of the spectra permitted the gamma-rays to be divided into two groups:

1) gamma transitions showing an intensity decrease on the way of the source preparation, and

2) gamma transitions the decrease of the intensity of which is independent of the source used in experiments. This is shown on the decay curves for the most intense gamma-lines in a low and high energy part of the spectra (Fig. 2).

These facts suggest the existence of an activity due to an isomeric state in $^{134}Pr$ . The 11 min half-life given in Fig. 5 for this state was estimated as a mean value of the half-lives of the above-mentioned gamma transitions in the $^{134}Pr$ - $^{134}Nd$ equilibrium source (Fig. 1).

It is to be pointed out that the majority of the gamma lines, seen in this experiment, is associated with the postulated isomeric state.

## 4. Gamma-Gamma Coincidence Measurements

Gamma-gamma coincidence measurements were carried out using two 25 cc Ge(Li) detectors oriented at $180^{o}$. A coincidence circuit with a time resolution of about 170 ns was used to select the coincidence events stored in the "Minsk-2" computer /9/. Figures 3 and 4 show coincidence spectra obtained simultaneously with eleven gating windows, seven of which were set on the photopeaks of interest. The last ones were set close to these photopeaks on the compton background associated with the more energetic gamma transitions permitting the spectra, for the compton distribution underlying the photopeaks in windows, to be corrected. Because of the short half-life of the isotopes and the low efficiency of the detectors used in the experiment, only the most intence and low energy gamma transitions could be observed with satisfactory statistics. Figures 3 and 4 show the coincidence spectra obtained by adding the counts of eight measurements.

## 5. Decay Scheme

The coincidence spectrum gated with the most intense 409.2 keV gamma transition (Fig. 4) revealed strong 409.2-639.6 and 409.2 - 556.2 keV cascades verifying the existence of the 409.2, 1048.8 and 965.3 keV levels[2,3,4]. The latter is supported by the 965.2 keV crossover transition.

The spectra (Figs. 3 and 4) gated with the 215.1, 556.2 and 639.6 keV suggest the 215.1 keV transition to be in coincidence both with the 556.2 - and 639.6 keV gamma-rays. Moreover, these spectra clearly indicate that the 215.1 keV transition is in coincidence with the 639.6 keV transition which, in turn, seems to be in cascade with the 987.4 keV transition. These facts indicate that there are very likely two levels of energies 1812.0 and 2071.1 keV, respectively. The first of these is populated only by the 215.1 keV gamma-ray and depopulated by the above mentioned gamma-rays of energies 763.2 and 846.6 keV. The second one is supported by the 987.4 keV crossover transition and by a 677.5 - 384.5 keV cascade revealed in the spectra corresponding to the coincidence with the 384.5 and 556.2 keV transitions (Fig. 4) and confirmed by the energy balance.

The 1643.0 keV level,via of which the 384.5 keV and 677.5 keV transitions cascade,additionally is supported by two gamma-rays of energies 594.2 and 1233.9keV.The latter, shown in Fig. 5 as a dashed line, is included in the decay scheme on the base of energy balance only.

In the spectra gated with the 409.2 and 639.6 keV (Fig. 4) a peak in a 973 -978 keV region is seen. Because this peak is relatively wide in the coincidence spectra and the 978.4 keV transition was assumed to be in cascade with the 639.6 keV transition, one can conclude that the 973.3 keV gamma-ray is in cascade with the 409.2 or 639.6 keV transition (absence in the coincidence spectrum with the 556.2 keV )locating a level at 1382.5 or 2022.1 keV .

The spectrum in coincidence with the 215.1 keV transition revealed a strong peak at a place of two unresolved gamma-rays of energies 331.6 and 334.5 keV. On the other hand, the spectra gated with windows set at these energies, seem to be identical (within the statistical error limits). Basing on this information we assumed that the 2027.1 keV state is fed by these two transitions which depopulate two levels of energies 2358.7 and 2361.5 keV. The last one seems to be supported by three gamma-rays observed in single gamma spectra (Fig. 1).

The tentative 2174.2 keV state was included in the decay scheme on the basis of the energy sum rule and consistency of the relative intensity decay rate.

The next probable level at 1691.6 keV is based on a weak indication of the 309.1 - 667.2 keV coincidence (not shown here) on intensity and energy sum rule.

The right part of the decay scheme, shown in Fig. 5, was constructed on the basis of the energy sum rules only. There are included only such transitions the decay rates of which are independent of the way of the source preparation and the relative intensity of which (related to the 409.2 keV) is increased in the $^{134}Pr$ - $^{134}Nd$ equilibrium source. It was concluded, therefore, that these transitions are associated with the $^{134}Pr$ ground state activity.

About 20% of the gamma transitions, observed in the single spectra, are not included in the decay sheme shown in Fig. 5.

## 6. Discussion

A rough estimation of the relative intensity of the annihilation radiation indicates that the $^{134}Ce$ ground state, within the statistical error limits, is not populated in the $\beta^+$ decay from the $^{134}Pr$ ground state. Because the $\beta^+$ transition to the $2^+$ first excited state of $^{134}Ce$ is the most intence one, the spin of the ground state of $^{134}Pr$ is restricted to the values 2 or 3. The 59th and 75th odd nucleons occupy in the neighbouring nuclei the $d_{5/2}$ and $s_{1/2}$ orbitals, respectively. Assuming the same orbitals for the odd nucleons in the odd - odd $^{134}Pr$ nucleus one could expect that the ground state of that would have a spin of 2 or 3 and positive parity/10/. The value of the 2 has been confirmed experimentally by Akstrom et al./11/. If one assumes that the 973.3 and 639.6 keV gamma transitions are in cascade (Fig. 5), the above mentioned assignments can be supported in this experiment.

The branching ratio of the two components depopulating the second excited state in $^{134}Ce$ is consistent with the systematics for even-even nuclei in this mass region [12-15]. According to this systematics it is belived the characteristics of this state to be $2^+$.

The extreme left-hand side of Fig. 5 shows the results obtained in the in-beam spectroscopy [3,4], where a ground-state quasirotational band up to $I^{\pi}=8^+$ has been indentified. The first two members of this band seen here are consistent with the $2^+$, $4^+$ assignments [2,3,4].

The excited state at 1862.9 keV, tentatively proposed on the basis of energy differences, can be compared with the third member of the ground band of energies 1862.4 [3] and 1864.1 keV [4] observed in the works on ( *HI* , *xn* ) and ( $\alpha$ , *xn* ) reaction, respectively. This level would be depopulated by two 480.4 and 814.1 keV gamma-rays with approximately equal intensity. The first of these is not reported by the work on the reactions mentioned above.

This fact may suggest that these transitions either have not been properly located in the decay scheme, and the transition energy agreement of the 814.1 keV with those (813.9, 814.8 keV) observed in the reaction is accidental, or there exists an adjacent level of another nature.

According to the proposed decay scheme and the intensity of the gamma-rays given in Table 1, one can conclude that the most of the decay of the postulated isomeric state goes to the highly excited states of $^{134}Ce$ . These data can indicate that the spin of the proposed isomer is $\geq$ 5.


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Table 1. Gamma-rays observed in the decay of $^{134}Pr$ and $^{134}Nd$ in equilibrium with the $^{134}Pr$ daughter. The gamma-ray intensity, calculated on the CDC-1600 computer, were measured ~ 30 min after the end of the chromatographic separation.

| Energy (keV) $E_\gamma$ | $\Delta E_\gamma$ | Relative intensity $^{134}Pr$ $I_\gamma$ | $\Delta I_\gamma$ | $^{134}Nd$ - $^{134}Pr$ (in equilibrium) $I_\gamma$ | $\Delta I_\gamma$ |
|---|---|---|---|---|---|
| 168.6 | 0.5 | 0.5 | 0.1 | weak | |
| 184.3 | 0.5 | 1.9 | 0.3 | " | |
| 188.9 | 0.5 | 1.4 | 0.2 | " | |
| 206.8 | 0.5 | 0.3 | 0.2 | " | |
| 215.1 | 0.2 | 9.7 | 1.0 | 6.8 | 1.0 |
| 230.9 | 0.4 | 1.0 | 0.2 | 1.0 | 0.3 |
| 293.5 | 0.5 | 1.2 | 0.3 | 0.3 | 0.1 |
| 299.0 | 0.5 | 0.5 | 0.2 | weak | |
| 309.1 | 0.3 | 3.8 | 0.5 | 1.0 | 0.2 |
| 331.6 | 0.6 | 7.4 | 1.0 | 1.9 | 0.5 |
| 334.5 | 0.6 | 7.3 | 1.0 | 2.3 | 0.6 |
| 384.5 | 0.4 | 4.9 | 0.6 | 2.2 | 0.3 |
| 392.0 | 0.6 | 0.4 | 0.1 | weak | |
| 409.2 | 0.1 | 100 | 11 | 100 | 11 |
| 417.5 | 0.5 | 2.5 | 0.4 | 1.5 | 0.4 |
| 429.5 | 0.4 | 2.4 | 0.3 | 1.2 | 0.2 |
| 446.7 | 0.6 | 0.4 | 0.2 | 0.3 | 0.1 |
| 480.4 | 0.6 | 1.3 | 0.3 | 0.6 | 0.2 |
| 517.6 | 0.5 | 3.1 | 1.0 | 2.1 | 1.0 |
| 556.2 | 0.2 | 14.0 | 1.7 | 15.1 | 1.8 |
| 594.2 | 0.3 | 1.7 | 0.3 | 0.7 | 0.2 |
| 639.6 | 0.2 | 25.0 | 2.7 | 13.8 | 1.6 |
| 644.5 | 0.4 | 1.8 | 0.3 | 1.0 | 0.3 |
| 667.2 | 0.3 | 2.5 | 0.5 | 0.5 | 0.3 |
| 677.5 | 0.2 | 5.1 | 0.8 | 2.7 | 0.5 |
| 685.7 | 0.5 | 1.0 | 0.4 | 0.6 | 0.3 |
| 718.0 | 0.5 | 1.1 | 0.5 | weak | |
| 763.2 | 0.2 | 4.4 | 0.6 | 2.4 | 0.4 |
| 786.6 | 0.5 | 1.0 | 0.3 | 0.3 | 0.2 |
| 794.5 | 0.5 | 0.4 | 0.2 | weak | |
| 809.2 | 0.5 | 0.4 | 0.2 | 0.4 | 0.2 |
| 814.1 | 0.5 | 1.1 | 0.3 | weak | |
| 846.6 | 0.5 | 2.6 | 0.4 | 1.2 | 0.8 |
| 965.2 | 0.2 | 14.1 | 1.6 | 15.0 | 1.8 |
| 973.3 | 0.2 | 9.6 | 1.2 | 6.0 | 0.9 |
| 978.4 | 0.2 | 5.7 | 0.7 | 3.4 | 0.6 |
| 1000.0 | 0.5 | 1.0 | 0.2 | 0.9 | 0.3 |
| 1062.2 | 0.5 | 0.5 | 0.2 | 0.2 | 0.1 |
| 1125.4 | 0.2 | 4.2 | 0.6 | 1.0 | 0.3 |
| 1162.8 | 0.5 | 0.5 | 0.2 | 0.6 | 0.2 |
| 1196.8 | 0.5 | 1.2 | 0.3 | 0.3 | 0.1 |
| 1213.3 | 0.6 | 0.5 | 0.1 | 0.3 | 0.2 |
| 1233.9 | 0.6 | 1.1 | 0.2 | 0.3 | 0.1 |
| 1312.0 | 0.7 | 1.7 | 0.7 | 0.8 | 0.2 |
| 1365.5 | 0.3 | 1.1 | 0.3 | 1.6 | 0.4 |
| 1493.9 | 0.3 | 4.0 | 0.6 | 5.2 | 0.7 |
| 1579.9 | 0.3 | 3.5 | 0.5 | 4.5 | 0.7 |
| 1904.1 | 0.3 | 7.4 | 1.0 | 10.1 | 1.3 |
| 1964.1 | 1.0 | 1.1 | 0.5 | 1.4 | 0.7 |
| 2136.0 | 2 | 8.0 | 1.0 | 10.8 | 1.6 |
| ~2233 | | 1.5 | 0.3 | 2.2 | 0.5 |
| ~2331 | | 2.1 | 0.4 | 2.9 | 0.5 |

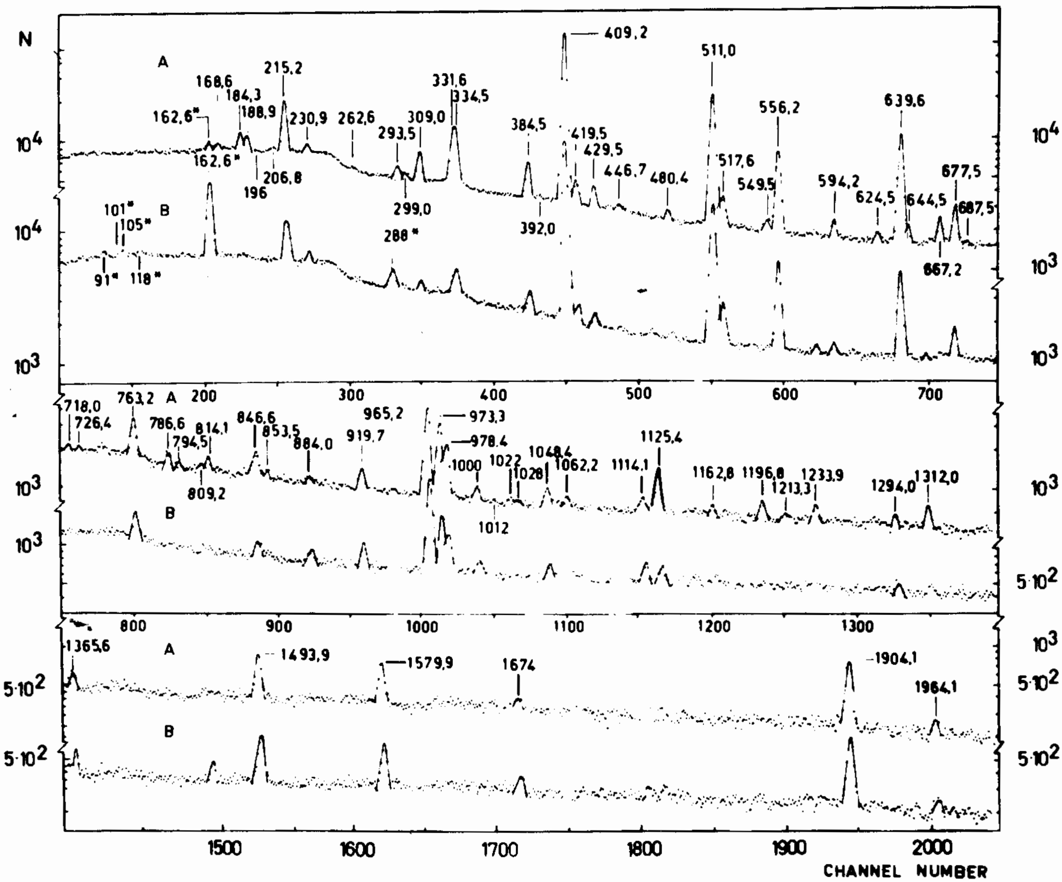


Fig. 1. Single gamma-ray spectra obtained by adding the counts of 4 measurements: A) the gamma-ray spectrum of $^{134}Pr$ , B) the gamma-ray spectrum of $^{134}Nd$ in equilibrium with the $^{134}Pr$ daughter. Gamma transitions corresponding to $^{134}Nd$ are labeled by crosses.

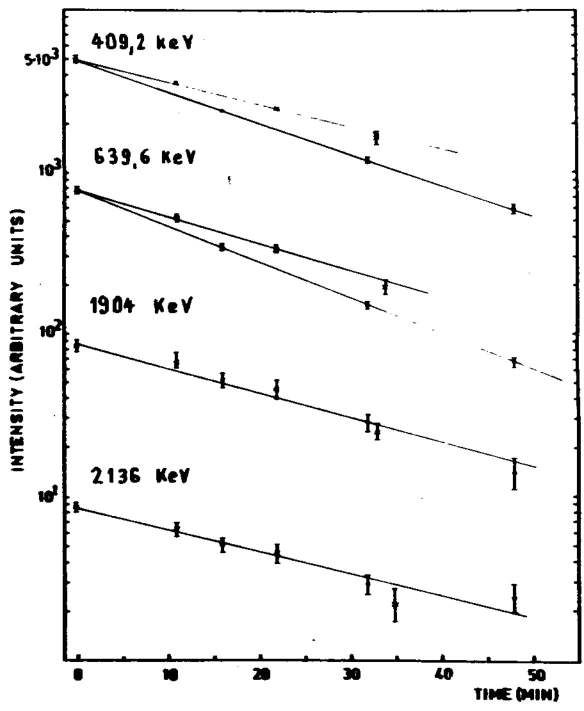


Fig. 2. Decay curves of the most intense gamma-rays associated with the $^{134}Pr$ (full circles) and $^{134}Pr$ in equilibrium with the $^{134}Nd$ parent (crosses), respectively.

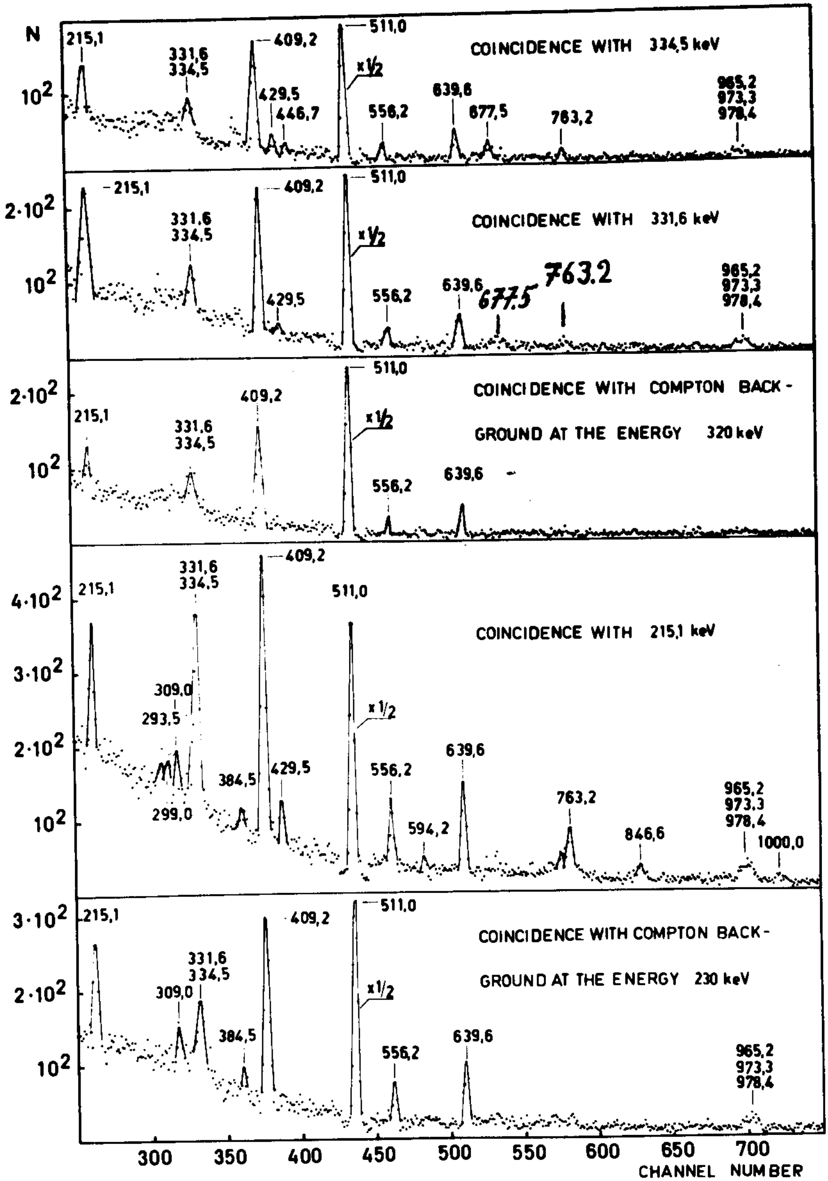


Fig. 3. Gamma-ray spectra in coincidence with the 215.1, 331,6 and 334.5 keV transitions. Spectra associated with gates set close to these photopeaks on the Compton background are also shown.

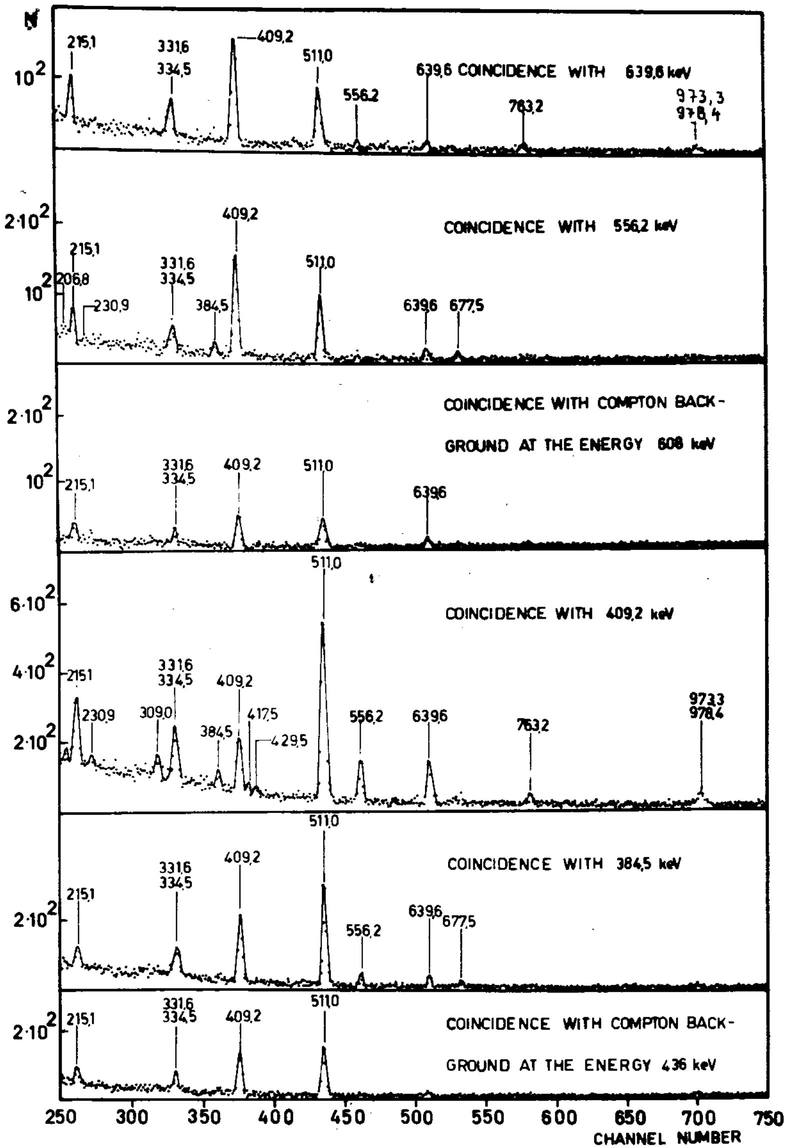


Fig.4. Gamma-ray spectra in coincidence with the 384.5, 409.2, 556.2 and 639.6 keV transitions. Gamma-spectra coincident with the Compton background are shown for comparison.

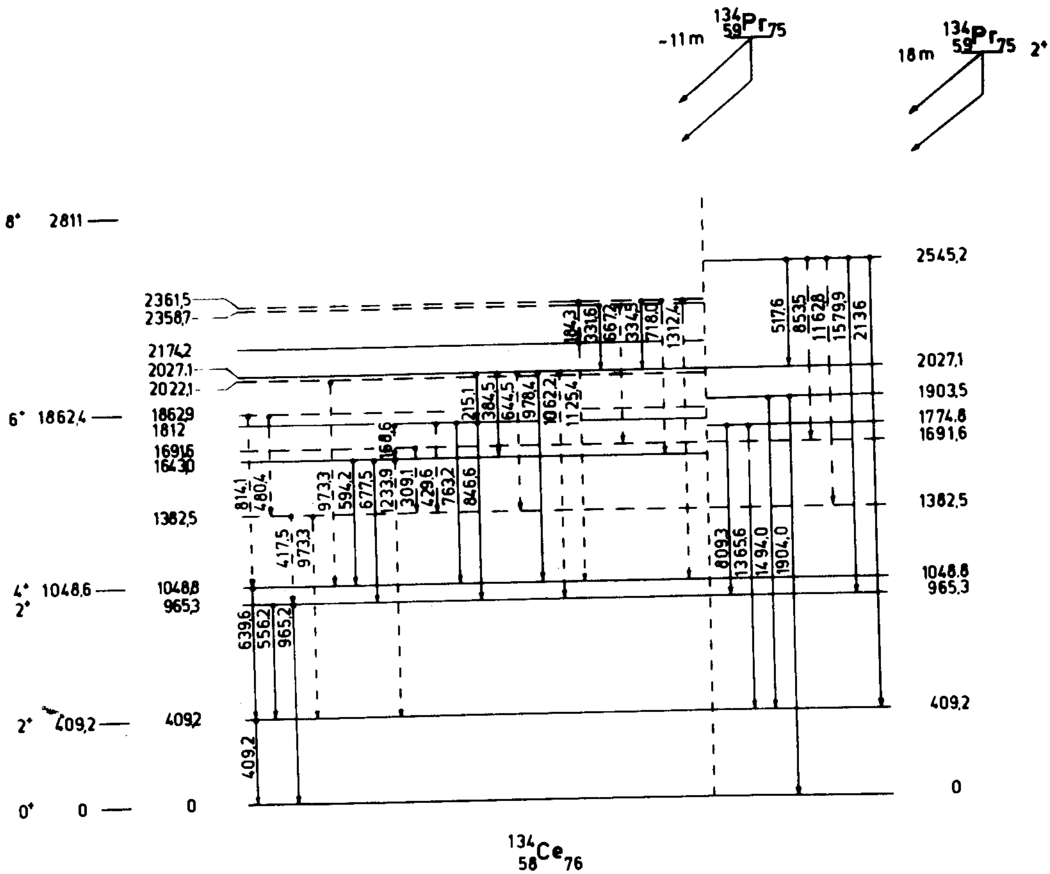


Fig. 5. Decay scheme proposed for $^{134}Pr$ . The decay scheme constructed only on the basis of the energy sum rules and proposed for the ground state of $^{134}Pr$ is shown at the right. The gamma transitions associated with the isomeric state, the placement of which in the decay scheme is suggested by $\gamma$ - $\gamma$ coincidence measurements, are labeled by full lines. Transitions labeled as dashed lines are included in the decay scheme on the basis of the energy sum rules.