Title
DECAY OF NEUTRON DEFICIENT EU, SM AND PM ISOTOPES NEAR THE PROTON DRIP LINE

Authors
Vierinen, K.S.
Nitschke, J.M.
Wilmarth, P.A.

Publication Date
1988-07-01

LBL-23221 c.2
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Submitted to Nuclear Physics A

Decay of Neutron Deficient Eu, Sm and Pm Isotopes Near the Proton Drip Line

K.S. Vierinen, J.M. Nitschke, P.A. Wilmarth,
R.B. Firestone, and J. Gilat

July 1988

NUCLEAR SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

DISCLAIMER

LBL-23221

DECAY OF NEUTRON DEFICIENT Eu, Sm and Pm ISOTOPES NEAR THE PROTON DRIP LINE

K.S. VIERINEN* , J.M. NITSCHKE, P.A. WILMARTH,

R.B. FIRESTONE AND J. GILAT**

Lawrence Berkeley Laboratory, University of California,

Berkeley, CA 94720

Abstract: The β–delayed proton and γ–ray decays of the two new isotopes ^{134,135}Eu and of ^{136}Eu, ^{134,135,136}Sm, ^{134,135,136}Pm and ^{135}Nd were studied. This is the first observation of β-delayed proton decay in europium isotopes. On-line mass separation and x-ray coincidences were used for isotope identification. Half-lives of 0.5±0.2 s and 1.5±0.2 s were measured for ^{134}Eu and ^{135}Eu respectively. For ^{136}Eu evidence for two isomers with half-lives of 3.7±0.3 s and ~3.0 s was obtained. Beta-delayed proton emission was assigned to the decays of ^{134}Eu, ^{135}Sm and ^{136}Eu based on proton K x-ray coincidences and mass separation. Proton branching ratios of $(9\pm3)\text{x}10^{-4}$ for ^{136}Eu and $(2\pm1)\text{x}10^{-4}$ for ^{135}Sm were measured. Beta-delayed proton emission to the 0^+ ground and to the 2^+ excited states in ^{134}Nd was observed following the ^{135}Sm decay. The ^{135}Eu activity was identified by Sm K_α x rays from its electron capture decay, and one γ ray was assigned to this decay. Fast allowed Gamow–Teller $0^+ \longrightarrow 1^+$ β transitions to the 118.9-keV level in ^{134}Pm and 114.4-keV level in ^{136}Pm were identified. The low-spin β decays of ^{136}Pm and ^{135}Nd were studied without significant interference from the high-spin decays, and decay schemes were constructed for ^{134,135,136}Sm, ^{134,135,136}Pm and ^{136}Eu.

* On leave from University of Helsinki, SF00180, Finland

** On leave from Soreq Nuclear Research Center, Yavne 70600, Israel

E

RADIOACTIVITY ^{134,135,136}Eu,Sm,Pm [from ^{92}Mo(^{46}Ti;xp,yn), E= 192–212 MeV mass separated sources]; measured $T_{1/2}$, β-delayed E_p, I_p, E_γ; deduced logft's; $\gamma\gamma$-, xγ-, $\beta\gamma$-, px-, pγ-coincidences; ^{135,136}Sm, ^{134,135,136}Pm, ^{134,135,136}Nd deduced levels, E, J, π ,level schemes. Detectors n-Ge, planar Ge, plastic scintillator, surface barrier Si(Au), ΔE-E telescope. Enriched targets.

1. Introduction

Beta-delayed particle and γ–ray emission, and direct alpha and proton decay are the main decay modes observed in radioactivity studies of extremely neutron deficient rare earth nuclei. Compound nucleus reactions followed by particle evaporation were used to produce several of these nuclides, which subsequently decay very slowly (on a nuclear time scale) by β decay to excited states in the daughter nuclei that subsequently deexcite by fast particle and/or γ–ray emission. From the studies of β–delayed particle and γ–ray emissions we have obtained information about half-lives, branching ratios, β-strength functions and nuclear structure[1]). In some cases it was also possible to infer nuclear properties of isomeric states and low-lying energy levels in the β–decay parents and daughter nuclei.

The nuclei reported in this paper — ^{134,135,136}Eu, ^{134,135,136}Sm, ^{134,135,136}Pm and ^{134,135,136}Nd — lie in the well deformed region between the N=82 and Z=50 closed shells. The shapes in this region are influenced strongly by the particles and holes in the high-j ($h_{11/2}$) shell structure; in this orbital the Fermi surface lies high for neutrons and low for protons. Proton particle/neutron hole configurations are typical for these nuclides. Because of this special shell structure, isomeric high- and low-spin pairs are expected to occur.

Other decay studies of the nuclei discussed in this paper can be found in refs.[1–10]). Recent high-spin in-beam reaction studies have been reported for ^{134,136}Nd[11]), ^{135}Pm[12]), ^{135}Nd[13]) and ^{134,136}Sm, ^{135}Pm [14]). The A=130-140 nuclides near the proton drip line have been investigated extensively during recent years. Interesting physical properties, which are peculiar to these nuclides, such as large deformations, superdeformation and triaxiality[11–14]) have been reported.

2. Experimental procedures

The activities were produced by bombarding a 1.85 mg/cm^2 foil of molybdenum, enriched in ^{92}Mo to 97.37%, with 204 MeV and 223 MeV ^{46}Ti ions at the Lawrence Berkeley Laboratory's SuperHILAC. The beam energies at the center of the molybdenum layer were calculated as 192-MeV and 212-MeV. These beam energies were selected to optimize the yield of the ^{134,135,136}Eu isotopes. The reaction products were mass separated on–line using the OASIS facility[2,15]) and deflected by an electrostatic mirror to a shielded room about 4 m above the separator that serves as a low background counting area. There the ions were collected by a programmable fast-cycling tape system and transported to a detector array for charged particle and photon spectroscopy.

Cross section calculations[16]) were used to determine the optimum bombarding energies. The total β–decay energies, Q_{EC}[17]), proton binding energies, S_p[17]), calculated cross sections[16]), and reaction channels for Eu and Sm isotopes are summarized in table 1. The calculated cross sections for the xn channels leading to ^{134,135,136}Gd were about 20, 20, and 100 μb, respectively. No evidence for Gd isotopes was observed in the experiments. The ^{134,135,136}Sm and ^{134,135}Pm isotopes were produced directly as evaporation residues as well as by β decay, while ^{136}Pm and ^{135}Nd were only produced by β decay. There were no interfering activities produced from other isotopes in the highly enriched ^{92}Mo target material since the yield of nuclides with A=134,135,136 from trace $A \geq 94$ molybdenum impurities is negligible.

A Si(Au) particle ΔE–E telescope and a thin planar hyperpure Ge x–ray detector faced the radioactive source on the tape, while a 1-mm thick plastic scintillator and a large, n-type Ge detector with a relative efficiency of 52.3% were located about 8 mm from the reverse side of the collection tape. The distances of the particle telescope and the x-ray detector from the tape were 5 and 15 mm respectively. A second 24.3% n-type Ge detector, was located about 45 mm from the radioactive source at 90° with respect to the other detectors. Energy and time signals as well as coincidences between particles, γ rays, x rays, and positrons, were recorded in a multiparameter event–by–event mode[18]). All events were tagged with a time signal for half–life identification. Singles data were measured with the 52.3% γ–ray and the hyperpure Ge x-ray detectors in a time-resolved, multispectrum mode with the tape cycle divided into eight equal intervals. The tape cycles used were 4 s for A=134, 16 s and 40 s for A=135, and 4 s and 16 s for A=136. During each tape cycle, new activity was deposited on the tape while the previously collected sample was counted; in all cases the collection time equalled the counting time. The distance between collection and measuring points was 175 mm and the transport time 65 ms.

Efficiency calibrations for the three Ge detectors were performed using radioactive standards in the same geometry as used during the experiment. Because of the very close geometry for the 52.3% Ge detector, the summing efficiency for cascading γ rays was also calibrated using radioactive standards. These summing effects were taken into account before quoting x–ray and γ–ray intensities. The smaller 24.3% Ge and planar Ge detectors were less subject to summing and were helpful in identifying the sum peaks caused by cascading γ and/or x rays in the 52.3% detector.

Absolute β intensities for each decay were determined by adding the intensities of the EC and β^+ decay. The EC intensities were derived from the K x-ray intensities correcting for fluorescence yield ω_K, $I_{EC(K)}/I_{EC}$ ratios, and internal conversion [19,20]), and the β^+ intensities were extracted from 511 keV annihilation γ rays. In each mass chain, the intensity of the 511 keV annihilation γ rays was decomposed into the intensities associated with the decay of each isotope using multicomponent decay analysis[21]). A correction for annihilation-in-flight[19]) was included. In calculating the β branchings, logft values and internal conversion corrections an M1 multipolarity was assumed for γ transitions with unknown multipolarities.

3. Results

3.1. DECAY OF ^{134}Eu, ^{134}Sm AND ^{134}Pm

3.1.1. $^{134}_{63}Eu_{71} \rightarrow ^{134}_{62}Sm_{72}$

Beta-delayed proton emission from ^{134}Eu was established on the basis of proton-Sm K_α x-ray coincidences. Half-life analyses for the protons were carried out with least squares[21]) and maximum likelihood methods. The former method gave $T_{1/2}$=0.5±0.2 s and the latter $T_{1/2}=0.4\pm^{0.3}_{0.1}$ s , resulting in an adopted half-life of 0.5±0.2 s for the β–delayed proton decay. The proton energy range was 2.2 MeV<E_p<6.0 MeV consistent with the predicted (Q_{EC}–S_p)=8.4 MeV[17]). Beta decay for both high-spin ($\pi h_{11/2}$) and low-spin ($\pi d_{5/2}$) states in ^{134}Eu was expected from the systematics of heavier odd-odd Eu isotopes. However, heavy-ion compound nucleus reactions at bombarding energies above the Coulomb barrier favor the production of high-spin isomers[22]). The observed β–delayed proton emission in ^{134}Eu, therefore, probably originates mainly from the high-spin isomer. Due to the small number of observed β–delayed protons no evidence for a second half–life component associated with the expected low-spin isomer could be obtained.

3.1.2. $^{134}_{62}Sm_{72} \rightarrow ^{134}_{61}Pm_{73}$

Bogdanov et al.[8]) observed Pm K x rays from EC decay for ^{134}Sm and measured a half-life of $T_{1/2}$=12±3 s for this activity. We observed nineteen γ rays following the β decay of ^{134}Sm. The 4-s time cycle was too short for an optimal half-life determination for this isotope, however, half-lives of 9±3 s for Pm x-rays and 11±3 s for the strongest γ rays were measured. From these two values a half-life of 10±3 s for ^{134}Sm was adopted, which is consistent with ref. [8]). The γ–ray spectrum observed with the 52.3 % Ge detector in coincidence with Pm K_α x rays is shown in fig. 1 a). Gamma-ray energies and intensities, and coincidence information are summarized in table 2. A partial level decay scheme for ^{134}Pm is shown in fig. 2. The even–even nucleus ^{134}Sm has a ground state spin J^π=0^+. Because of the low cross section for the production of ^{134}Eu compared to ^{134}Sm (see table 1) the latter was produced predominantly as an evaporation residue. This is confirmed by the absence of any growth component in the decay of the ^{134}Sm activity, indicating that the ^{134}Eu intensity was very weak.

In calculating positron intensities for the decays of ^{134}Sm and ^{134}Pm, the 4-s tape cycle was too short for a reliable multicomponent decay analysis of the 511-keV intensity, so $\gamma\gamma$- and γx- coincidence data together with cross section calculations (table 1) were used to confirm the adopted β^+ intensities. The EC intensity in ^{134}Sm decay (calculated from Pm K x rays) was 35(15)% of the total β-decay intensity. This high EC/β^+ ratio with respect to observed β intensity to low-lying levels in ^{134}Pm may mean that there is strong β feeding to high-lying levels in ^{134}Pm or that there exists unidentified highly converted γ transitions in ^{134}Pm. An intensity of 60±15 per 100 β decays for the 118.9-keV transition in ^{134}Pm was measured, which gives a logft of ~4.6. Internal conversion corrections were made for the 118.9-keV transition assuming that it has an M1 multipolarity. The logft value is consistent with an allowed Gamow–Teller $0^+ \longrightarrow 1^+$ β transition[20]) suggesting a spin of $J^\pi=1^+$ for the 118.9-keV level. There may also be considerable β feeding to the levels at 229.2 and 419.0 keV for which tentative $J^\pi=1^+$ assignments were made. There may be considerable unobserved γ-ray feeding to all levels due to the limited detector efficiencies, and only lower limits for the logft values to the highest levels and the ground state were calculated. About 20% of the expected β intensity from ^{134}Sm decay was not placed in the decay scheme, and due to the high EC/β^+ ratio main part $\geq$15% was placed to high lying unobserved levels. The spin value most likely for the ^{134}Pm ground state is 2^+ based on its γ-decay and on the β-decay properties (fig. 2) and level systematics of Z=61 and N=73 nuclei[19]). The β-branching limit of <5% (logft>5.6) estimated to the ground state of ^{134}Pm doesn't rule out a spin assignment of (1^+) for this level.

3.1.3. $^{134}_{61}Pm_{73} \rightarrow ^{134}_{60}Nd_{74}$

Bogdanov et al.[8]) observed Nd K x rays from the EC decay of ^{134}Pm, assigned 4 γ rays to this decay, and reported a half-life of 24±2 s. A partial level scheme for ^{134}Nd from ^{134}Pm decay was reported recently by Kortelahti et al. [9]), by Kern et al. [6]), Béraud et al.[7]), and Gilat et al.[2]). Half-lives of 22.6±0.5 s and ~5 s for high-spin and low-spin isomer in ^{134}Pm, respectively, were reported by Kern et al. [6]).

We assign 21 γ rays to the decay of ^{134}Pm. The γ–ray data are summarized in table 2, and the γ–ray spectrum observed with the 52.3 % Ge detector in coincidence with Nd K_α x rays is shown in fig. 1 b). A partial decay scheme is given in fig. 3. The positron intensity for ^{134}Pm was calculated by subtracting the ^{134}Sm β^+ intensity from the total β^+ intensity observed in A=134 mass chain. The half-life analysis of 511-keV annihilation radiation and Nd K x rays showed no short components (<3 s). A half-life range of 3 s<$T_{1/2}$<20 s was estimated for the low-spin isomer based on the decay of 294.4-keV γ-ray and on reasonable logft limits of 4.5<logft<5.9, when allowed β-transitions[20]) were assumed to the first two 2^+ levels in ^{134}Nd. The spin assignments in the decay scheme are based on our measurements and those in refs. [5,12,14,15]). The 4-s tape cycle was too short to confirm the published half-life values[6,8,9]). The half-life of 22.6±0.5 s measured by Kern et al.[6]) was used in our analysis for the high-spin isomer. A higher β^+/EC=3±1 intensity ratio than in the ^{134}Sm decay was observed which is consistent with the predicted[17]) larger Q_{EC} value for ^{134}Pm (assuming a similar β-strength distribution).

Based on the systematics of heavier odd-odd Pm isotopes, it is expected that ^{134}Pm has low-lying J^π=1^+, 2^+ and 5^+ levels. The β decay of 0^+ (even-even) ^{134}Sm predominantly feeds the low-spin 1^+ levels in ^{134}Pm as discussed in the previous chapter. The heavy–ion compound nucleus reaction produces mainly the high-spin isomer in ^{134}Pm. However, from the intensity balances of γ rays from low- and high-spin levels in ^{134}Nd it was estimated that 40% of the ^{134}Pm β decay is from the low-spin and 60% from the high-spin isomer. This can be explained by the strong low-spin population from ^{134}Sm (0^+) parent. Based on this estimate, the decay scheme shown in fig. 3 was constructed. In ^{134}Nd the 4^+ and 6^+ members of the ground state collective band are populated by β decay with logft values of $\geq$5.9. This suggests a $J^\pi=5^+$ for the high-spin ^{134}Pm parent. The low-spin $J^\pi=(2^+)$ state of ^{134}Pm would predominantly populate the 2^+ and 3^+ states in ^{134}Nd, and since its half-life could not be resolved from the radioactivities of mass A=134 products, a direct measurement of logft values in the decay of ^{134}Pm (2^+) was not possible. A β-branching limit of <10% with logft>6.5 for the low-spin decay to the (0^+) ground state of ^{134}Nd is consistent with a 2^+ assignment for the low-spin parent state in ^{134}Pm. For the logft calculations in the decay scheme (fig. 3), the 22.6 s half-life was used for both the low- and high-spin decays. The spin assignment of $J^\pi=2^+$ for the 753.8-keV level was based on the systematics of 2_2^+ states in even Nd isotopes and its strong deexcitation to both the 2_1^+ and the 0^+ level. (The subscripts indicate the order of different spin levels as a function of increasing excitation energy.) For the levels at 1089.1 and 1313.7 keV, spin values of $J^\pi=3_1^+$ and 4_2^+, respectively, are suggested, based on the constructed level scheme and on the systematics. The 2_2^+, 3_1^+, 4_2^+ levels appear to be members of a γ-vibrational band, consistent with the level systematics of the even-even Nd, Sm and Ce isotopes (see discussion)[2,19]. Our suggested level scheme for ^{134}Nd agrees with the published results[6,7,9]) with the exception of a few transitions which were not observed in our measurements or were assigned as background peaks.

3.2. DECAY OF ^{135}Eu, ^{135}Sm, ^{135}Pm and ^{135}Nd

3.2.1. $^{135}_{63}Eu_{72} \rightarrow ^{135}_{62}Sm_{73}$

The isotope ^{135}Eu was observed for the first time and identified by Sm K_α x rays following its EC decay. A half-life of 1.5±0.2 s was measured for the Sm K_α x rays. A weak γ ray at 120.8 keV with a half-life of <10 s, seen in the 16-s but not in the 40-s tape cycle, was assigned to ^{135}Eu β decay based on coincidences with Sm K x rays. It is also possible that Sm K x rays are associated with an isomeric transition in ^{135}Sm (unobserved in this measurement). However, in our measurements the Sm K x rays were observed in coincidence with positrons which would rule out an isomeric transition.

The calculated Q_{EC} value for ^{135}Eu decay is 8.7 MeV[17]) and the proton binding energy in ^{135}Sm is 3.3 MeV[17]). Proton emission is therefore energetically possible, but from the systematics of β–strength functions no strong β–delayed proton decay was expected for this isotope (see discussion)[1]). The low cross section for producing ^{135}Eu (see table 1) and interfering protons from ^{135}Sm decay may obscure a possible weak β-delayed proton branch in ^{135}Eu.

3.2.2. $^{135}_{62}Sm_{73} \rightarrow ^{135}_{61}Pm_{74}$

Bogdanov et al.[8]) observed Pm K x rays from EC decay of ^{135}Sm and β-delayed protons. In our experiments, twenty-four β-delayed γ rays in addition to the delayed protons were measured. A single component half-life of 10.3±0.5 s was observed for the Pm K x rays, β–delayed protons, and the strongest γ rays. This agrees with the published result of 10±2 s[8]). Beta-delayed protons with an energy range of E_p=1.9–5.0 MeV were measured and assigned to the ^{135}Sm decay on the basis of proton-Pm K_α x-ray coincidences. About 60% of the protons were in coincidence with the known $2^+ \longrightarrow 0^+$ 294.4-keV transition[14]) (see ^{134}Pm decay in this paper) in ^{134}Nd. However, less than about 10% of the protons were in coincidence with the 494.9-keV $4^+ \longrightarrow 2^+$ transition. Statistical model calculations[1]) of these branchings indicate that spin values of 3/2 - 7/2 are the most probable for the ^{135}Sm proton precursor. Bogdanov et al.[8,10]) assigned a spin of $7/2^+$ to the proton precursor using statistical model arguments. This was, however, done without the consideration of proton γ-ray coincidences. A proton branching ratio of $(2\pm1)\text{x}10^{-4}$ was derived for the proton precursor by comparing the number of protons with the number of β decays determined from the Pm K x rays and from the 10.3 s time component of the annihilation radiation. Consistent proton branching ratios were observed in both 16-s and 40-s tape cycles. The experimental proton branching ratio, within the error limits, was predicted with statistical model calculations[1]) if spin values of 3/2 or 5/2 were assumed for ^{135}Sm. Isomer pairs with $1/2^+$, $3/2^+$ and $5/2^+$ low-spin and $11/2^-$ high-spin levels have been observed in other heavier odd-mass Sm isotopes[7,19]) and in odd-mass N=73 isotones. However, no γ rays in ^{135}Pm from the low-spin isomer decay of ^{135}Sm were identified. There may be an isomeric transition in ^{135}Sm or a strong β transition to the low-spin ground state in ^{135}Pm from the low-spin isomer of ^{135}Sm. Neither one of these possibilities were confirmed directly in our experiments.

Fig. 4 a) shows the Pm K_α x-ray coincident γ–ray spectrum measured with the 52.3 % Ge detector. The published low-lying E_γ=285.9-keV transition within a rotational band from the $15/2^-$ to the $11/2^-$ level was seen[12,14]) (see fig. 5), which indicates that we are observing β decay from a high-spin ($9/2^-$ - $11/2^-$) isomeric state in ^{135}Sm. Only high-spin levels were identified and shown in the tentative ^{135}Pm level scheme (fig. 5).

The intense 55.4-keV transition was assigned to de-excite the $11/2^-$ level in ^{135}Pm based on γ-γ coincidence data and intensity balances. This transition was not reported in the high-spin structure studies[12,14]). Two intense, low-energy transitions in ^{135}Pm at 49.1 keV and 104.6 keV are assigned to deexcite the low-lying second excited level in ^{135}Pm. The 55.4-keV γ ray must have a multipolarity of M1 or E2 to balance the level scheme of ^{135}Pm (Fig. 5). The 77-keV transition is placed twice in the level scheme (fig. 5), however, on the basis of the coincidence information the intensity of the 77-keV transition from the 418.2-keV level is weak. The 236.6-keV γ transition is a doublet and on the basis of the coincidence data equal intensities were assigned to the 236.6-keV transitions from the 418.2-keV and 341.3-keV levels. The intensity of 77-keV γ-ray peak shows a clear two component decay. One of the components, with a half–life of 10.3 s, is assigned to ^{135}Sm decay. The second component (also in coincidence with Pm x rays) has a half–life of 2.4±0.9 s; the origin of this transition is unclear, since all other γ rays identified with the ^{135}Sm decay have a half–life of about 10 s in agreement with the Pm x rays and β–delayed protons. One possibility is that this transition is related to the low-spin isomer β decay of ^{135}Sm. The γ rays assigned to ^{135}Sm decay are listed in table 3. For the β-branching and logft calculations in fig. 5 it was assumed that the high-spin isomer decay represents 100% of the β-decay intensity.

3.2.3. $^{135}_{61}Pm_{74} \rightarrow ^{135}_{60}Nd_{75}$

Bogdanov et al.[8]) reported five γ rays associated with ^{135}Pm decay, and Alkhazov et al.[8,10]) observed 33 γ rays. The half-life of ^{135}Pm in the literature is 49±7 s [8,10,19]). We assign 39 γ rays to this decay (figs. 4, 6 and table 3) of which 33 were placed in the decay scheme shown in fig. 7. Seventeen of the in-beam γ rays assigned to ^{135}Nd in ref. [23]) were also observed in our experiments.

The 463.5-keV level reported by Alkhazov et al.[8,10]) was not confirmed by our measurements. We assigned the 463.8-keV γ ray to a transition de-exciting the 1176.7-keV level. Our half-life analysis was complicated by the fact that the low-spin isomer of ^{135}Pm is fed by the decay of ^{135}Sm. The strong 128.8-keV ($3/2^+ \rightarrow 1/2^+$) and 198.8-keV ($11/2^- \rightarrow 9/2^-$) γ rays in ^{135}Pm decay had different time dependences (fig. 8). The 198.8-keV γ ray decayed mainly with a single–component half–life of 49±3 s consistent with the expected direct production of the high spin state of ^{135}Pm in heavy-ion reaction. The 128.8-keV γ ray showed a clear growth and decay pattern. The two component (growth and decay) half-life analysis indicated a 10±3 s growth and a 45±10 s decay. Similar growth and decay was also observed for the other low-spin γ rays 208.1-, 245.0-, 262.9-, 270.0-, 282.1- and 398.7-keV. These transitions showed a systematic increase in their intensities relative to the 198.8-keV transition when the tape cycle was changed from 16 s to 40 s. The growth and decay pattern was also observed for Nd K x rays. The growth and decay time dependences are consistent with population of low-spin levels in ^{135}Nd by β decay of the low-spin isomer in ^{135}Pm, which is fed by a ^{135}Sm parent. Further studies with different tape-cycles and reactions are needed to complete and confirm these tentative parent-daughter relations. The γ-ray intensities in table 3 and decay schemes (figs. 5 and 7) are average values from the 16-s and 40-s tape cycles. The β branchings and logft values in fig. 7 were calculated assuming equal intensities for high-spin and low-spin isomer decays.

The nuclide ^{135}Nd was not produced directly, but was observed as the β-decay daughter of ^{135}Pm. The γ rays from ^{135}Nd were characteristic of the decay of a high-spin isomer to ^{135}Pr with intensities similar to those reported in the literature[10,19]). However, two new intense γ rays with energies of 422.2 and 556.1 keV were observed. The intensity of the 422.2-keV γ ray was enhanced relative to high-spin γ rays in the 40-s tape cycle compared to the 16-s cycle, consistent with a possible growth and decay pattern. This may indicate feeding of a low-spin isomer in ^{135}Nd from the ^{135}Pm low-spin β decay. These new transitions are in coincidence with Pr K x rays and are probably associated with the decay of a low-spin isomer in ^{135}Nd. Our results seem to contradict an experiment where transitions with similar energies were assigned to levels in ^{135}Nd using the ^{122}Te(^{16}O,3nγ) reaction[10,23]).

3.3. DECAY OF ^{136}Eu, ^{136}Sm AND ^{136}Pm

3.3.1. $^{136}_{63}Eu_{73} \rightarrow ^{136}_{62}Sm_{74}$

The ^{136}Eu activity was first observed by Alkhazov et al. [3]), but assigned to ^{136}Sm decay. The decay of ^{136}Eu was briefly reported in ref. [4]) by Mlekodaj et al. and in ref. [5]) by Vierinen et al.. Decay schemes for ^{136}Eu β decay have been proposed by Kern et al.[6]), by Béraud et al.[7]) and by Gilat et al.[2]).

We observed β-delayed proton and γ–ray emission for this isotope[2]). From the proton decay a half-life of 4±1 s was determined and the proton energy range was 2.2 MeV<E_p<5.6 MeV. Twenty-six γ rays were assigned to ^{136}Eu β decay on the basis of coincidences with Sm K_α x-rays or other known γ rays and by half-life (fig. 9 and 10, and table 4). A proton branching ratio of $(9\pm3)\text{x}10^{-4}$ was measured relative to the absolute β intensity calculated from Sm K x rays and from the 3.7 s component of the 511-keV annihilation radiation. Consistent branching ratios for protons were obtained from both 4-s and 16-s tape cycles. During the 4-s time cycle only Sm K_α x rays were observed in coincidence with protons. However, in the 16-s tape cycle, both Pm and Sm K_α x rays were seen in coincidence with protons. Since ^{136}Sm is not a proton precursor because of the small (Q_{EC}–S_p) window of only ~1 MeV[17]), the probable explanation for Pm K_α x rays coincident with ^{136}Eu protons is a highly converted transition in ^{135}Pm fed by β-delayed proton emission. Strong β feeding was observed to the 255.1-keV 2^+ level and the 8^+ level was also populated in ^{136}Sm which suggests an isomer pair in ^{136}Eu. It is probable that both high- and low-spin isomers in ^{136}Eu are proton precursors, since the final nucleus ^{135}Pm have both high- and low-spin low-lying levels available.

A half-life of 3.7±0.3 s was measured both for Sm K x rays, and the 255.1-keV $2^+ \longrightarrow 0^+$ transition in ^{136}Sm, while for the 431.7-keV $4^+ \longrightarrow 2^+$ transition a half–life of 3.3±0.3 s was observed. The ground state rotational band in ^{136}Sm was populated up to the $J^\pi=8^+$ level at E_x= 1797.1 keV. This is consistent with a (6^+,7^+) high–spin ^{136}Eu parent. The decay scheme based on our coincidence measurements is presented in fig. 11. Our results agree for the most part with the published level scheme of ^{136}Sm[6,7]), however, we propose β decays from two isomeric species since we observe apparent strong β feedings to the 8^+, 6^+, 4^+, 3^+ and 2^+ states in ^{136}Sm. For ^{136}Eu spin assignments of (6^+,7^+) and (3^+) for the high- and low-spin isomers, respectively, were adopted. For the high-spin isomer of ^{138}Eu a spin value of 7^+ has been suggested[6,7]). However, if there is unobserved γ feeding to the 8^+ level in ^{136}Sm, the (5^+,6^+) spin values for the high-spin isomer in ^{136}Eu can not be ruled out.

A second 2^+ state was established at E_x=713.0 keV in ^{136}Sm. The level at 1490.9 keV (2^+) has not been reported in the literature and the 778.0-keV transition was placed into this level instead of the previously proposed 1034.6-keV state[6]). The low- and high-spin decays of ^{136}Eu were separated analogously to ^{134}Pm. The low- and high-spin β-decay intensities were estimated to be 85% and 15% respectively (tape cycle 16s). The 255.1-keV $2^+ \longrightarrow 0^+$ transition in ^{136}Sm dominates the spectrum in fig. 9 a) indicating a strong β feeding to this level. Its total β intensity was measured in a similar way to the proton branching ratio and a resultant logft value of $\sim$5.4 was obtained, assuming β decay only from the low-spin parent state. The allowed nature[20]) of this transition suggests a spin of 1^+, 2^+ or 3^+ for the low-spin ^{136}Eu parent, and the low-limit on its β feeding to the ^{136}Sm ground state (logft>6.8) is in agreement with these spin assignments. The logft limit of >5.5 for the 6^+ level and of >5.2 for the 8^+ level in ^{136}Sm in the high-spin decay are consistent[20]) with the (7^+) assignment for the high-spin ^{136}Eu parent. Statistical model calculations predicted well, within the error limits, the observed proton branching ratio, if most of the observed β-delayed proton intensity was assigned to the low-spin (3^+) β-decay parent. More complete decay scheme and proton γ-ray coincidence information are needed to confirm the spin assignments for the isomers in ^{136}Eu parent. A list of γ rays and their relative intensities assigned to ^{136}Eu decay are presented in table 4.

3.3.2. $^{136}_{62}Sm_{74} \rightarrow ^{136}_{61}Pm_{75}$

Altogether 41 γ rays associated with the decay of ^{136}Sm were observed (see table 4). Identification was made through Pm K x-ray and/or γ–γ coincidences (see figs. 9 and 10). Our results indicate, that 12 of the 18 previously assigned γ rays[3]) do not belong to the decay of ^{136}Sm. Gamma rays with energies of 234, 255 and 668 keV, previously assigned to ^{136}Sm[3]), are associated with ^{136}Eu decay. Our results agree with the partial decay scheme in refs. [6,10]), however, some new levels and γ transitions have been added. The 977.4-keV level[6]) was not seen in our measurement and we reassigned the 483.5-keV γ ray, which was previously placed from this level[6]), to ^{136}Eu decay.

The β-decay daughter of ^{136}Sm is the odd–odd nucleus ^{136}Pm and, consequently, the level structure is complex as is shown in fig. 12. Many low energy γ rays of comparable intensity were observed. The 114.4-keV transition has an intensity (corrected for internal conversion and assuming an M1 multipolarity) of 80$\pm$20 relative to 100 β decays which is more than the other γ-ray intensities added together. This γ transition was therefore assigned to the first excited state in ^{136}Pm. The spectrum observed with the 52.3% detector gated with the 114.4-keV transition is presented in fig. 10 b). For the 114.4-keV level a logft$\sim$4.6 was calculated indicating an allowed Gamow-Teller transition[20]) from the J^π=0^+

ground state of ^{136}Sm. A similar logft value was estimated by Kern et al.[6]) for this β transition. Therefore a $J^\pi=1^+$ assignment was made for the 114.4-keV level. The low limit on β feeding to the ground state of ^{136}Pm from ^{136}Sm decay with a logft limit of >6.2 which is consistent with a 2^+ or 3^+ assignment for the low-spin ^{136}Pm parent. The spin 2^+ was adopted for this low-spin isomer on the basis of ^{136}Pm decay scheme and the analysis of ^{136}Pm decay discussed in the next section.

3.3.3. $^{136}_{61}Pm_{75} \rightarrow ^{136}_{60}Nd_{76}$

In the reactions ^{92}Mo(^{46}Ti;xp,yn) ^{136}Pm was produced only indirectly by the β decay of ^{136}Sm. In previously published results[10,19]) of the decay of ^{136}Pm the 4^+, 5^+ and 6^+ states in ^{136}Nd were observed to be populated by Gamow-Teller β transitions, and a spin assignment of (5^+) was made for the parent ^{136}Pm. The (5^+) ^{136}Pm β-decay parent was not observed in our measurement, because it was not produced directly by the heavy-ion reaction. However in our experiment ^{136}Sm β decay populates only the low-spin isomer of ^{136}Pm so high-spin states $J^\pi \geq 6^+$ in ^{136}Nd are not observed. This is first experiment, where the low-spin isomer decay of ^{136}Pm has been measured independently. Only 4^+, 3^+ and 2^+ levels in ^{136}Nd were populated (see fig. 13). Compared to the published results [10,19]) the relative intensity of the $2^+_2 \longrightarrow 0^+$ 862.2-keV transition was enhanced from 8% to about 28% relative to the $2^+_1 \longrightarrow 0^+$ 373.7-keV transition. At the same time the relative intensities of the transitions from the 4^+ levels were strongly diminished. Similar changes in relative γ-ray intensities are observed by comparison of our results to those reported recently by Kern et al. [6]). The energies (in keV) and relative intensities (in parenthesis) of the strongest γ rays normalized to the intensity of the 373.7-keV (=100)[10,19]) transition were: 488.6 (22), 602.6 (17), 679.3 (2.9), 857.2 (15) and 862.2 (28). The strong enhancement of the transitions from 2^+ levels and the population of 2^+, 3^+ and 4^+ states in ^{136}Nd suggests a 2^+ or 3^+ low-spin isomer in ^{136}Pm. The β intensity of ^{136}Pm was estimated from the ^{136}Sm decay and considerable β feeding with allowed logft values only to the 2^+ and 3^+ excited states of ^{136}Nd was apparent. This indicates a probable 2^+ assignment for the low-spin ^{136}Pm parent, which is also supported by the ^{136}Sm decay results. The 2^+ spin assignment disagrees with the 2^-,$3^\pm$ spin values for the ^{136}Pm low-spin isomer suggested recently by Kern et al.[6]). The used 4-s and 16-s tape cycles were too short for a half-life determination for (2^+) ^{136}Pm. A lower limit of 30 s (fig. 13) is based on the decay analysis of 373.7-keV γ-ray intensity. An upper limit of 150 s (fig. 13) was estimated assuming allowed β transitions to 2^+ and 3^+ levels in ^{136}Nd.

4. Discussion

The odd–odd nuclides ^{134,136}Eu are the first europium isotopes observed to decay by β–delayed proton emission. Beta-delayed proton emission was expected since (Q_{EC}-S_p)$\geq$5 MeV and the proton precursors have odd neutron numbers. Beta-delayed proton emission in the region of A=120-150 and N<82 has been observed almost exclusively from odd-N precursors[1]). In the even-odd proton precursor ^{135}Sm, protons were observed coincident with the $2^+ \longrightarrow 0^+$ ground state γ transition of even-even ^{134}Nd implying a 3/2-7/2 precursor spin, while in odd-odd precursor decays such as ^{136}Eu and ^{134}Eu the proton decay populates many levels in the more complex odd-even final nucleus and intense proton γ-ray coincidences are not seen. The measured half–lives of 0.5 s for ^{134}Eu, 1.5 s for ^{135}Eu, and 3.7 s + ($\sim$ 3 s) for ^{136}Eu are in good agreement with the gross theory estimates of 1, 2, and 2 s by Takahashi et al.[24]). A 17 s half–life has been predicted, from the experimental average β–strength systematics of heavier odd-odd Eu isotopes, for the high-spin decay of ^{136}Eu[25]) and a 10 s half–life was predicted for ^{135}Eu[25]). These half-life estimates are considerably larger than the measured values. The half-life extrapolations depend, however, very sensitively on Q_{EC} and details of nuclear structure effects expressed in the β-strength function.

For ^{136}Eu, (^{135}Sm) and ^{134,135,136}Pm β decays from isomeric pairs were observed which is consistent with the established systematics of isomeric states in odd-odd Eu, even-odd Sm, odd-odd Pm and odd-even Pm isotopes[7,19,26]). The excitation energies and the order of the β-decaying isomers were not determined. In ^{135}Nd the low-spin isomer ($1/2^+$) was placed to the 64.9-keV level and high-spin isomer $9/2^-$ to the ground state. In the known nuclei the energy gap between the low- and high-spin isomers is small and isomeric transitions were not observed since the large spin and small energy differences of these isomeric levels makes their intensity weak. In odd-mass Eu and Pm isotopes the excitation energy of the high-spin isomer is systematically decreasing from the N=82 shell towards more neutron deficient nuclei. For odd-mass Z>50 and N=73 isotones the energy of the high-spin isomer decreases as a function of increasing proton number. An extrapolation of these level systematics suggests possible high-spin ground states for ^{135}Eu, ^{135}Sm and ^{135}Pm[7,19]).

The β decay of the $J^\pi=0^+$ ground state of ^{134}Sm strongly populates the 118.9-keV level in ^{134}Pm and the allowed β transition (logft$\sim$4.6) confirms the $J^{\pi}=1^{+}$ spin assignment for this level. The analogous transition to the 114.4-keV 1^{+} level in ^{136}Pm (logft$\sim$4.6) populated by the 0^{+} parent state in ^{136}Sm was also observed. These logft values are lower than typical for allowed low-spin β transitions in the rare earth nuclei far from the N=82 shell[19,26]). The measured low logft values are due to the $\pi h_{11/2} \longrightarrow \nu h_{9/2}$ spin-flip transition and indicate similar deformations for β-decay parent proton and β-decay daughter neutron states[26]).

In the ^{134,136}Pm decays the expected second 2^{+} states were found just below the first 4^{+} levels in ^{134,136}Nd. This is typical of heavier even-even neutron-deficient Nd isotopes. The energy difference of the second 2^{+} and the first 4^{+} level in neutron-deficient Nd isotopes decreases systematically as a function of increasing deformation and decreasing neutron number (fig. 14 a)). In ^{132}Nd ref. [9]) the 2_2^{+} level was moved upwards in energy and observed about 213 keV above the 4_1^{+} state. This signifies a change in deformation to a less γ-soft shape between neutron numbers 74 and 72. This effect is not seen in the even Sm isotopes (fig. 14 b)), but there is a weak indication for it in even Ce isotopes.

Comparison of our results with the high-spin structure studies of ^{134}Nd, ^{136}Nd, ^{135}Pm, ^{135}Nd and ^{134,136}Sm, ^{135}Pm[11−14,27]) shows that in β-decay some of the side feedings to the ground state band are observed, and in the even-even nuclei the lowest members of the γ-vibrational bands are identified. Additional strong low-energy γ transitions could be identified in these decay schemes, which was usually not possible in the high-spin structure experiments (see ^{135}Sm and ^{135}Pm decays and refs. [12−14])). The β decay of very proton-rich nuclei where levels with spins similar to the parent nucleus spin are preferentially populated can provide complementary information to the in-beam level structure studies.

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098. One of the authors K.V. wishes to thank the National Research Council for Sciences, Academy of Finland and University of Helsinki Finland for support. We express our thanks to the staff of the SuperHilac accelerator of the Lawrence Berkeley Laboratory, and L. Archambault and A. Wydler for their excellent and efficient cooperation.

References

1) J.M. Nitschke, P.A. Wilmarth, J. Gilat, P. Möller and K.S. Toth, Proc. 5th International Conference on Nuclei Far from Stability, Ontario, ed. I.S. Towner, (1987) 697

2) J. Gilat, J.M. Nitschke, P.A. Wilmarth, K. Vierinen and R.B. Firestone, ibid. 463

3) G.D. Alkhazov, K.A. Mezelev, Yu.N. Novikov, V.N. Panteleyev, and A.G. Polyakov; V.P. Afanasyev, N. Ganbaatar, K.Ya. Gromov, V.G. Kalinnikov, J. Kormicki, A. Latuszynski, A. Potempa, J. Sieniawski, F. Tarkanyi, and Yu.V. Yushkevich, Z. Phys. **A305** (1982) 185

4) R.L. Mlekodaj, G.A. Leander, M.O. Kortelahti, B.D. Kern, R.A. Braga, C.P. Perez, and B.E. Gnade, Bull. Am. Phys. Soc. **31** (1986) 836

5) K. Vierinen, J.M. Nitschke, P.A. Wilmarth, J. Gilat, and R.B. Firestone, University of Helsinki, Department of Physics, Finland, Annual Report (1986) 51

6) B.D. Kern, R.L. Mlekodaj, G.A. Leander, M.O. Kortelahti, E.F. Zganjar, R.A. Braga, R.W. Fink, C.P. Perez, W. Nazarewicz, and P.B. Semmes, Phys. Rev. **C36** (1987) 1514, and Proc. 5th International Conference on Nuclei Far from Stability, Ontario, ed. I.S. Towner, (1987) 441; and B.D. Kern, R.L. Mlekodaj, M.O. Kortelahti, R.A. Braga and R.W. Fink, Z. Phys. A **330** (1988) 37

7) R. Béraud, A. Charvet, R. Duffait, A. Emsallem, J. Genevey, A. Gizon, M. Meyer, N. Redon, and D. Rolando-Eugio, Proc. 5th International Conference on Nuclei Far from Stability, Ontario, ed. I.S. Towner, (1987) 445; and N. Redon, T. Ollivier, R. Béraud, A. Charvet, R. Duffait, A. Emsallem, J. Honkanen, J. Genevey, A. Gizon and N. Idrissi, Z. Phys. **A325** (1986) 127

8) D.D. Bogdanov, A.V. Demyanov, V.A. Karnaukhov, L.A. Petrov, A. Plohocki, V.G. Subbottin, and J. Voboril, Nucl. Phys. **A275** (1977) 229; and G.D. Alkhazov, V.P. Afanasev, N. Ganbaatar, K.Ya. Gromov, V.G. Kalinnikov, Ya. Kormitski, A. Lyatushinski, K.A. Mezelev, Yu.N. Novikov, V.N. Panteleev, A.G. Polyakov, A. Potemka, E. Senyavski, F. Tarkani and Yu.V. Yushkevich, 32nd Ann. Conf. Nucl. Spectr. Struct. At. Nuclei, Kiev, (1982) 78

9) M. Kortelahti, E.F. Zganjar, R.L. Mlekodaj, B.D. Kern, R.A. Braga, R.W. Fink, and C.P. Perez, Z. Phys. **A327** (1987) 231

10) Yu.V. Sergeenkov, Nucl. Data Sheets **52** (1987) 205, and T.W. Burrows, Nucl. Data Sheets **52** (1987) 273

11) E.S. Paul, C.W. Beausang, D.B. Fossan, R. Ma, W.F. Piel, Jr. P.K. Weng, and N. Xu, Phys. Rev. **C36** (1987) 153; and E.S. Paul, S. Shi, C.W. Beausang, D.B. Fossan, R. Ma, W.F. Piel, Jr., N. Xu and P.K. Weng, Phys. Rev. C36 (1987) 2380

12) C.W. Beausang, L. Hildingsson, E.S. Paul, W.F. Piel, Jr., P.K. Weng, N. Xu and

D.B. Fossan, Phys. Rev. **C36** (1987) 602

13) E.M. Beck, F.S. Stephens, J.C. Bacelar, M.A. Deleplanque, R.M. Diamond, J.E. Draper, C. Duyar, and R.J. McDonald, Phys. Rev. Lett. **58** (1987) 2182

14) C.J. Lister, B.J. Varley, R. Moscrop, W. Gelletly, P.J. Nolan, D.J.G. Love, P.J. Bishop, A. Kirwan, D.J. Thornley, L. Ying, R. Wadsworth, J.M. O'Donnell, H.G. Price and A.H. Nelson, Phys. Rev. Lett. **55** (1985) 810

15) J.M. Nitschke, Nucl. Instr. and Meth. **206** (1983) 301

16) W.G. Winn, H.H. Gutbrod and M. Blann, Nucl. Phys.**A188** (1972) 423

17) S. Liran and N. Zeldes, At. Data Nucl. Data Tables **17** (1976) 431B

18) R.A. Belshe and M.K. Lee, Nucl. Instr. and Meth. **A253** (1986) 65 and R.A. Belshe, EVA reference manual, (Lawrence Berkeley Laboratory, Berkeley), PUB-3062, (1987), unpublished

19) C.M. Lederer and V.S. Shirley, Table of Isotopes, (Wiley, New York, 1978), and E. Brown and R.B. Firestone, Table of Radioactive Isotopes, (Wiley, New York,1986); and G. Azuelos and J.E. Kitching, At. Data Nucl. Data Tables **A10** (1971) 205

20) S. Raman and N.B. Gove, Phys. Rev. **C7** (1973) 1995, and N. Gove and M.J. Martin, Nucl. Data Tables **10** (1971) 206

21) K. E. Gregorich, Ph. D. thesis, (Lawrence Berkeley Laboratory, Berkeley), LBL-20192, (1985) p.108, unpublished

22) K.J. Moody and J.J. Hogan, Phys. Rev. **C34** (1986) 899

23) J. Gizon, A. Gizon, M.R. Maier, R.M. Diamond, F.S. Stephens, Nucl. Phys. **A222** (1974) 557

24) K. Takahashi, M. Yamada and T. Kondoh, At. Data and Nucl. Data Tables **12** (1973) 101

25) M. Nowicki, D.D. Bogdanov, A.A. Demyanov, and Z. Stachura, Acta Phys. Polonica **B13** (1982) 879

26) J. van Klinken and S.J. Feenstra, Phys. Rev. **C12**, (1975), 2111

27) R.J. McDonald, private communication

TABLE 1

The total EC-decay energies Q_{EC}[17]), proton binding energies S_p[17]) and cross sections[16]) for the studied Eu, Sm and Pm isotopes

Nuclide	Q_{EC} (MeV)	S_p [a]) (MeV)	Bombarding energy (MeV)	Reaction channel	Cross section[b]) (mb)
^{134}Eu	11.4	3.1	212	(^{46}Ti,p3n)	0.8
^{135}Eu	8.7	3.3	192	(^{46}Ti,p2n)	6.2
^{136}Eu	10.3	3.7	192	(^{46}Ti,pn)	1.4
^{134}Sm	5.7	1.8	212	(^{46}Ti,2p2n)	26.0
^{135}Sm	7.4	2.0	192	(^{46}Ti,2pn)	80.0
^{136}Sm	4.7	2.4	192	(^{46}Ti,2p)	2.3
^{134}Pm	8.7	4.8	212	(^{46}Ti,3pn)	100.0
^{135}Pm	6.0	4.9	192	(^{46}Ti,3p)	62.0
^{136}Pm	7.7	5.3	-	-	-

[a]) Proton binding energy in β-decay daughter nucleus.
[b]) Ref. 16.

TABLE 2

Energies, intensities, and coincidences of γ transitions in ^{134}Sm and ^{134}Pm decays

^{134}Sm β decay			^{134}Pm β decay		
Energy (keV)	Relative γ intensity	Coincident[b]) γ transitions	Energy (keV)	Relative γ intensity	Coincident[b]) γ transitions
			294.4(2)	100(10)	335,459, 495,516,524, 560,609,631,795,1167, 1247,1375,1443
50.8(5)	1.0(3)				
104.7(3)	2.4(5)		335.3(3)	4.5(10)	294, 459,754
107.0(5)[a])	0.9(3)		459.4(2)	14.1(15)	294,560,851
110.3(3)	10(2)	51,119	494.9(2)	54(5)	294, 524,631,1167,1443
112.4(3)	7(2)	117,219	516.0(3)	7.1(10)	
116.8(3)	3(1)		524.4(3)	5.2(10)	294,495
118.9(2)	100(10)	110,130,141,161, 186,219,257,300,380	559.9(3)	10.0(15)	294,459,754
			594.7(4)	0.9(4)	
129.5(5)	2.3(5)	119,161	597.2(3)	3.5(10)	
141.3(4)[a])	3.2(5)	119	608.6(3)	5.2(10)	294, 495,795
161.1(4)	11(3)	119,219,257	631.2(2)	14.2(15)	294,495
185.9(3)	7.2(20)	119	753.8(2)	15.1(15)	335,560
219.0(2)	28(5)	51,110,112,119, 161,229,280	794.7(2)	19.1(15)	294,516,609
			851.3(3)	2.4(5)	
224.0(4)[a])	1.8(5)		1167.1(3)	5.6(15)	294,495
229.2(3)	12(4)	51,219	1247.4(4)	3.0(10)	294
257.4(3)	6.4(20)	110,119,161	1375.0(5)	1.8(5)	294
280.0(3)	13(4)	219	1384.0(5)	1.5(5)	
300.0(2)	18(4)	119	1442.6(5)	3.6(10)	294
380.1(2)	16(5)	119	1640.0(5)[a])	0.9(5)	
419.0(3)	8.8(25)		1706.0(5)[a])	1.0(5)	

[a]) Not placed in the level scheme.

[b]) Strong transitions are underlined.

[c]) β^+ intensity from 511 keV annihilation radiation.

TABLE 3

Energies, intensities, and coincidences of γ transitions in ^{135}Sm and ^{135}Pm decays

^{135}Sm β decay

Energy (keV)	Relative γ intensity	Coincident[b]) γ transitions
49.1(2)	10(3)	55,77,237,428
55.4(2)	65(20)	49,77,126,237,286,363
77.2(2)[c])	33(10)	49,55,77,105,237,428
104.6(2)	46(10)	77,237,428
115.5(3)	8(2)	
123.8(3)[a])	6(2)	
126.3(2)	88(10)	55,237,350,428, 544,573,1132
159.5(4)	3(1)	55,77,126,182
181.7(2)	22(5)	237,428
190.3(2)	100(10)	286
236.6(3)[c])	90(30)	55,77,105,126
285.9(2)	87(10)	55,190
313.4(4)	10(3)	
341.3(2)	~7	
350.0(2)	20(5)	126
363.0(2)	84(10)	55
418.2(2)	26(5)	
428.2(2)	70(10)	49,55,77,105,126
543.5(2)	26(5)	126
573.0(2)	30(8)	
754.7(2)	40(10)	
1132.1(5)	22(5)	

^{135}Pm β decay

Energy (keV)	Relative γ intensity	Coincident[b]) γ transitions
98.1(2)	8(2)	208,245,342,464
128.8(2)	66(15)	134,177, 249,270,342, 357,394,409,464,519
135.5(5)[c])	4(1)	129,263
177.4(3)	6(1)	129,342,464
190.6(5)	~2	208,464
198.8(2)	100(10)	362, 365,464, 519,978,1016,1159
208.1(2)	50(15)	98,191, 342,440, 464,471
219.9(3)	6(3)	464,493
245.0(4)[a])	9(3)	342,493
249.3(3)	11(3)	129, 270,399,464
262.9(2)	50(15)	136
270.0(2)	43(15)	129,249,464
282.1(2)	30(5)	325
306.2(2)	35(5)	129,342,464
324.6(2)	10(3)	
341.9(2)	20(5)	98,129,177, 208,306,464
357.0(4)[a])	6(2)	
362.2(2)	17(3)	199
365.4(4)	6(3)	199
394.2(3)	10(5)	129
398.7(2)[c])	40(10)	208,249,464
409.2(2)	15(5)	129
439.9(4)	7(3)	208
463.8(2)	64(5)	98,129,199,208,220,249, 270,306,342,713
471.2(3)	9(2)	208
493.2(2)	30(5)	220,464
518.3(4)[a])	8(3)	129
523.3(3)	9(3)	
560.8(3)	12(3)	
564.2(3)	22(5)	
582.8(3)[a])	11(3)	
713.0(2)	30(5)	464
978.0(2)	40(5)	199
1016.2(2)	11(3)	199
1078.0(5)[a])	10(5)	
1159.0(5)[a])	6(2)	
1176.7(3)	33(5)	

[a]) Not placed in the decay scheme.

[b]) Strong intensity γ transitions are underlined.

[c]) Doublet peak, placed twice in the decay scheme.

TABLE 4

Energies, intensities, and coincidences of γ transitions in ^{136}Eu and ^{136}Sm decays

^{136}Eu β decay			^{136}Sm β decay		
Energy (keV)	Relative γ intensity	Coincident[b]) γ transitions	Energy (keV)	Relative γ intensity	Coincident[b]) γ transitions
109.1(4)[a])	1.0(5)		90.0(4)[a])	1.7(5)	
211.8(4)[a])	2.5(5)		91.1(5)[a])	0.6(2)	
234.0(5)[a])	0.4(2)		100.2(5)[a])	0.8(2)	
255.1(2)	100(10)	432,458, 484,535,540 576,584,778,1236	114.4(2)	100(10)	141,172,185,186,192,314,351, 371,377,380,449,516,748,1260
284.0(5)[a])	0.3(1)	458,576	116.1(4)	1.1(5)	123,183,307
320.1(3)	2.0(5)		123.4(3)	6(1)	116,141,163,183,192 270,299
384.0(5)[a])	0.4(2)				
431.7(2)	34(5)	255,484,535,576	128.8(5)	0.6(2)	185,299
457.3(3)	3(1)	255,458	134.9(4)	1.4(2)	90,91,114,129,141,207,314
458.0(2)	20(5)	255,457	135.5(5)[a])	0.2(2)	114,163
483.5(3)	3(1)	255,432	140.6(3)	~1	
534.7(2)	10(3)	255,432	141.4(4)	1.2(5)	114,123,135,163,172,287
540.0(4)[a])	0.9(3)		163.3(4)	1.5(3)	123
544.0(3)[a])	3(1)		170.0(5)	0.6(1)	
575.6(2)	7(3)	255,535	172.4(3)	2.3(5)	114,141
583.9(3)[a])	7(2)		183.2(3)	2.1(5)	123
592.7(3)[a])	7(2)		185.0(3)	1.9(5)	114,129,186
660.6(5)[a])	~3		186.1(4)	0.6(1)	114,185,299, 377
668.5(5)[a])	~4		192.0(4)[c])	2.7(5)	114,123
696.0(3)[a])	4(2)		200.7(5)	0.7(1)	114
713.0(2)	17(5)		206.9(5)	1.5(5)	100,135
778.0(2)	17(5)	255,458	221.2(5)	1.5(5)	
815.0(4)[a])	4(1)		270.4(4)[a])	1.8(5)	
1001.0(3)[a])	10(5)		276.3(5)	0.8(2)	
1236.0(4)	3.0(5)		286.8(2)	12(3)	141,276,516
1490.9(5)	3.0(5)		299.3(4)[c])	8(1)	123,129,186,380
			306.6(4)	1.6(3)	
			313.6(2)	13(3)	114,135
			350.5(3)[a])	2.1(5)	
			371.0(5)	1.8(5)	114,371
			377.0(4)	2.5(5)	114,186,299,371,485
			380.0(3)	2.0(3)	
			422.6(3)	2.4(3)	
			448.7(3)	2.7(3)	114
			485.3(2)	14(3)	377
			515.6(5)	0.4(1)	
			555.5(4)	1.8(4)	
			747.7(2)	15(2)	114
			802.4(4)	7(2)	
			1260.0(5)[a])	~2	

[a]) Not placed in the decay scheme.

[b]) Strong intensity γ transitions are underlined.

[c]) Doublet.

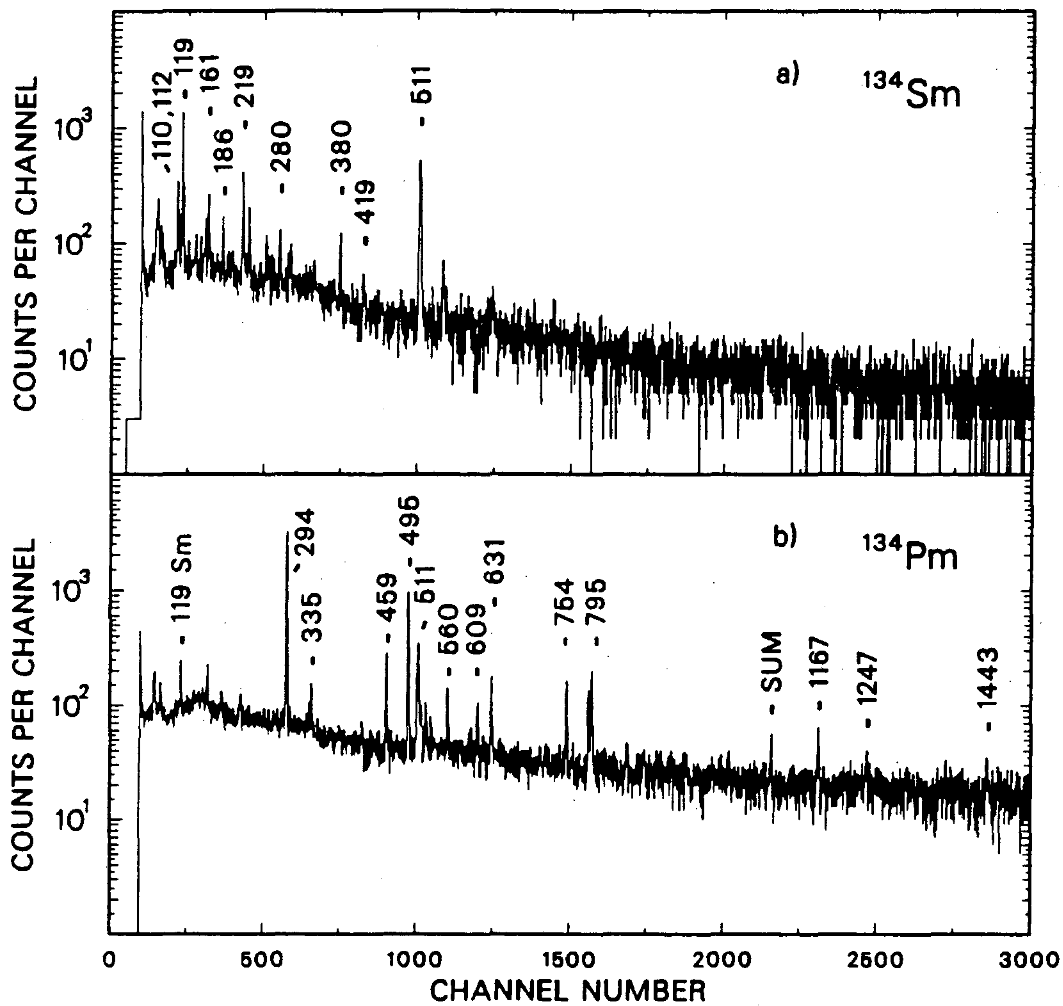

Fig. 1. The γ-ray spectra associated with the decay of ^{134}Sm and ^{134}Pm measured with the 52.3% Ge detector in coincidence with Pm and Nd x rays are presented in a) and b), respectively. Gated background spectra were subtracted. The energies of the marked peaks are in keV.

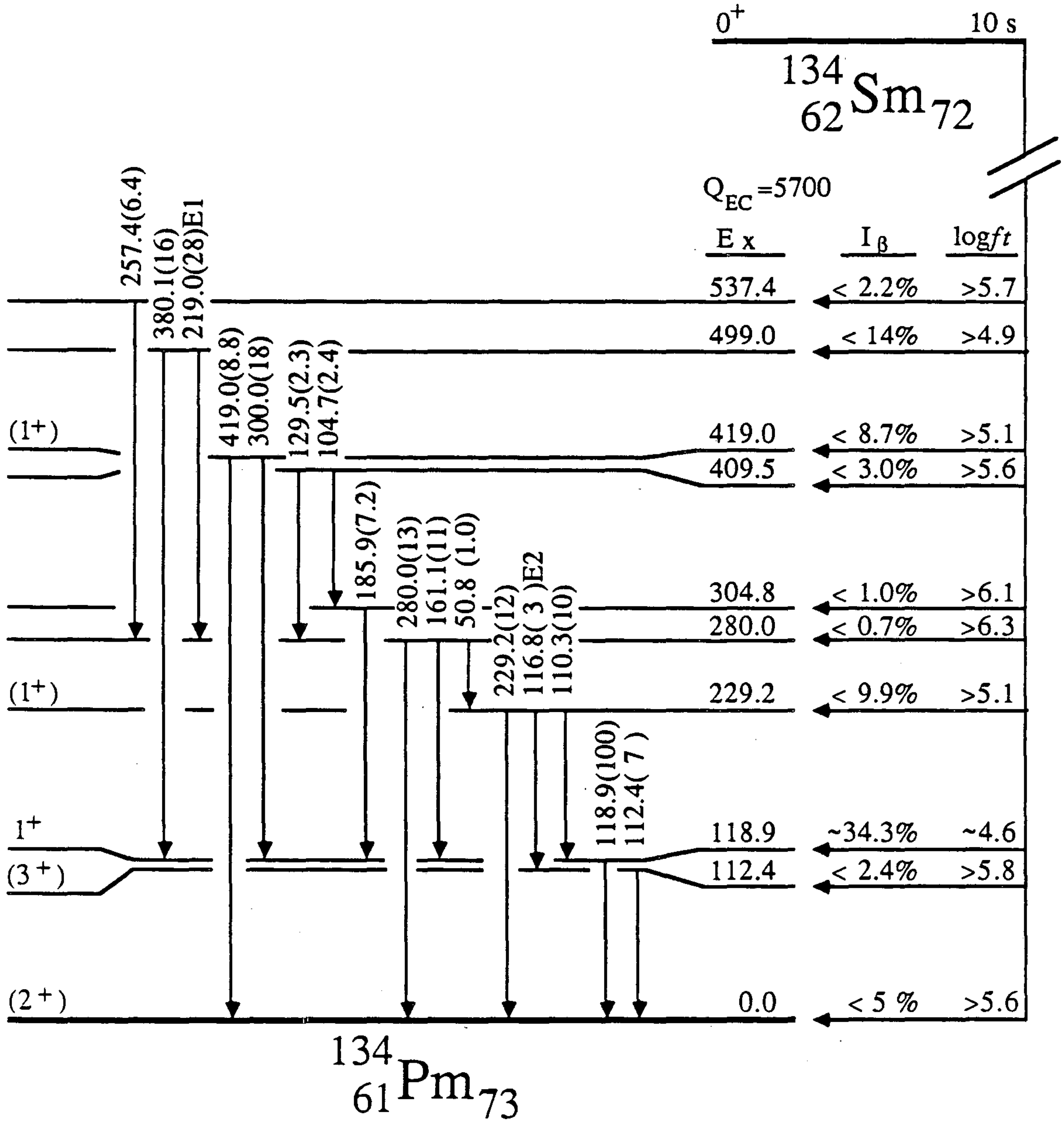

Fig. 2. The decay scheme of ^{134}Sm. The β branchings I_β are given relative to 100 β decays and the γ intensities are relative to 100 decays of the 118.9-keV γ ray (internal conversion corrections were not included in the γ-ray intensities). The multipolarities of transitions are shown if they are different from the assumed M1. The excitation (E_x) and γ-ray energies, and Q_{EC} are in keV.

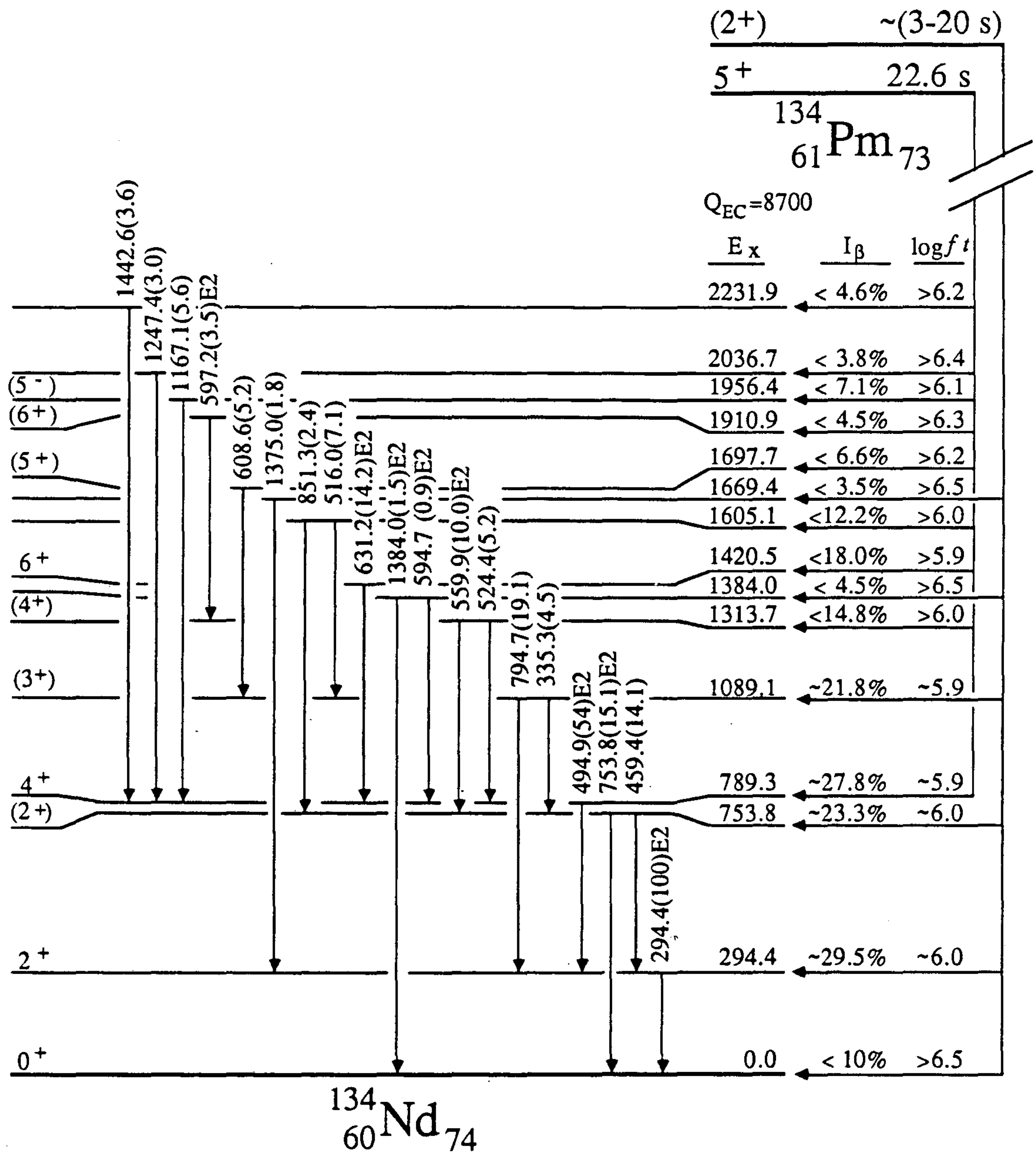

Fig. 3. The decay scheme of ^{134}Pm. The units are same as in the fig. 2. A half-life of 22.6 s for both the low- and high-spin decays was used for logft calculations. The β-decay intensities of the two isomeric states were separated. Gamma-ray intensities are given relative to the 294.4-keV transition. The relative position of the high- and low-spin isomers in ^{134}Pm is not known.

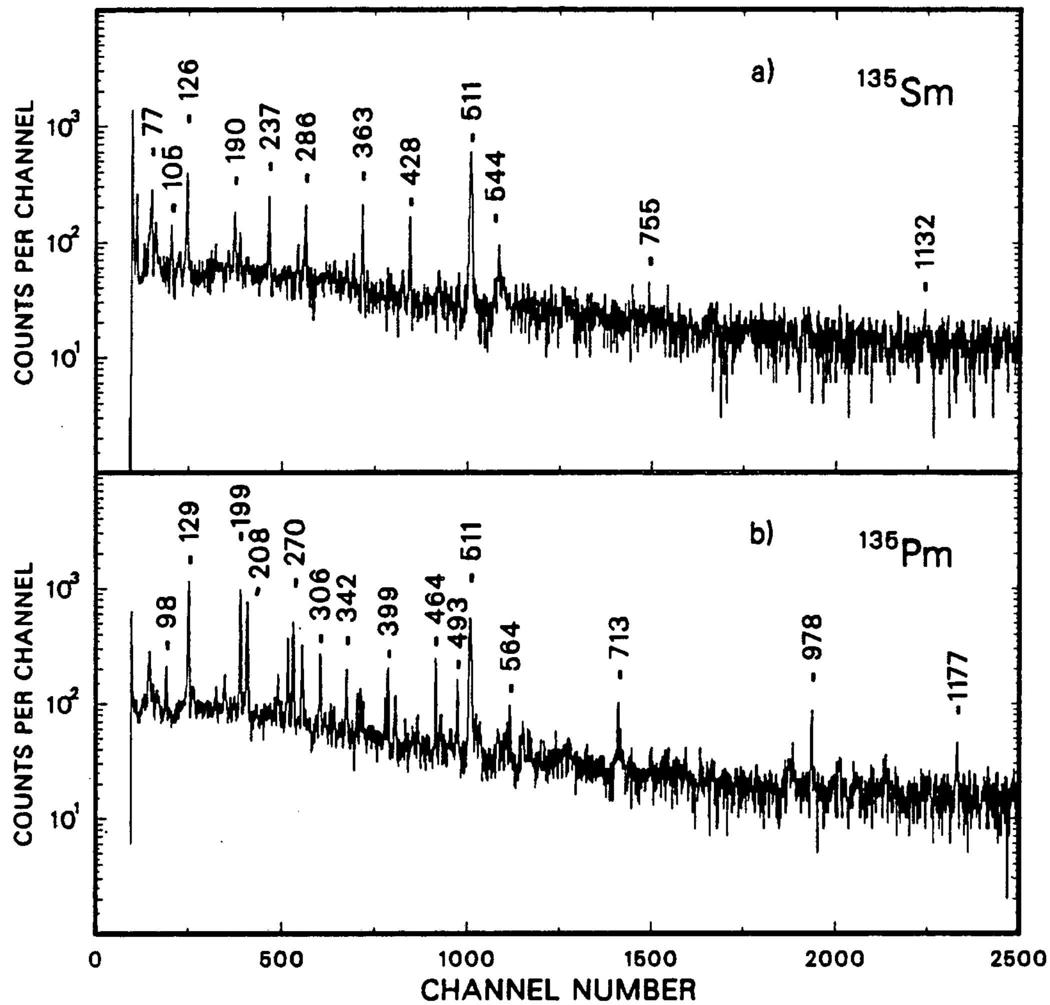

Fig. 4. The Pm and Nd K x-ray coincident γ-ray spectra associated with the decay of ^{135}Sm and ^{135}Pm measured with the 52.3% Ge detector are presented in a) and b), respectively. Gated background spectra were subtracted.

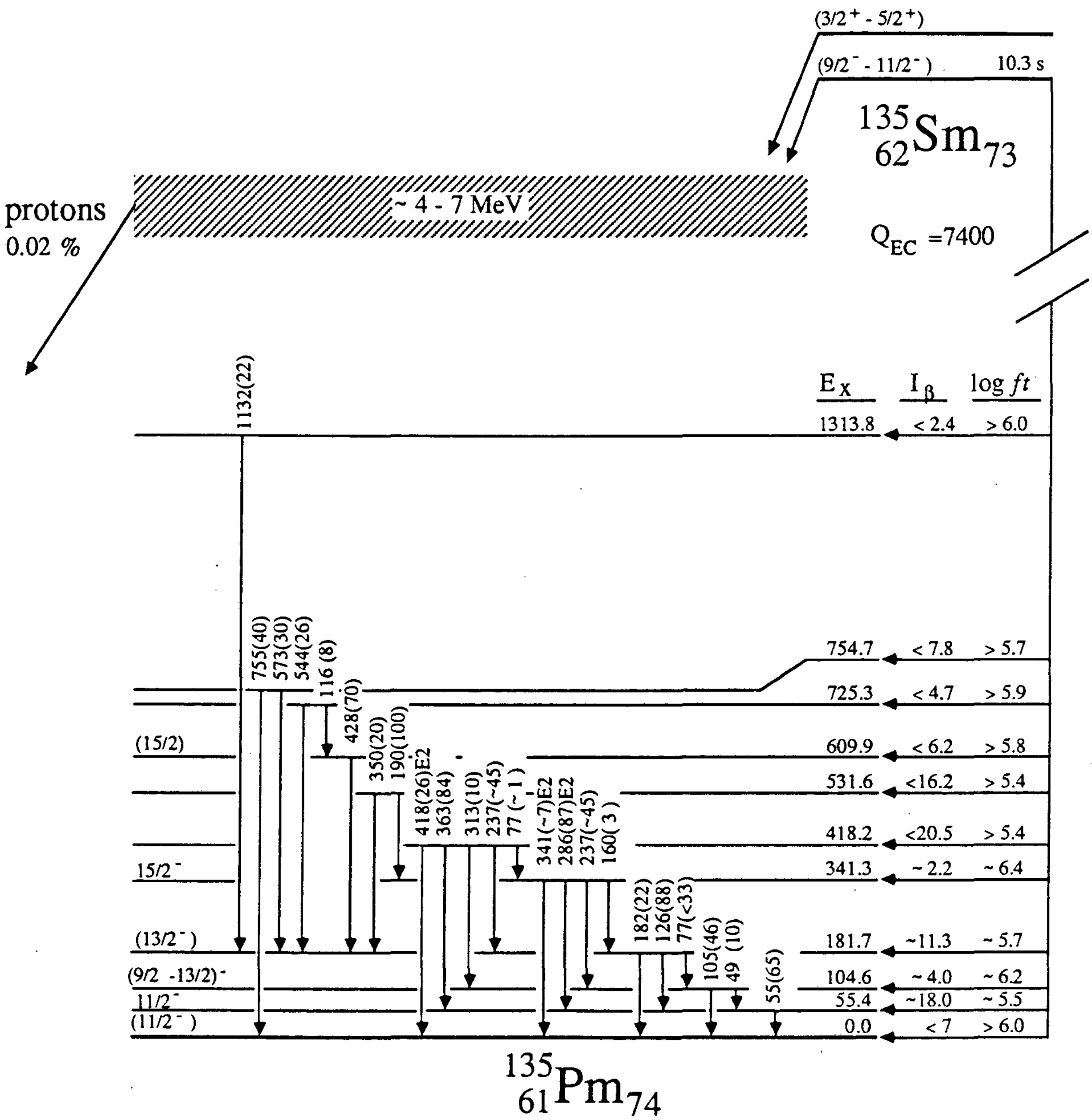

Fig. 5. Tentative decay scheme of ^{135}Sm. The energy and intensity units are the same as in fig. 2. All β-decay intensity was assumed to originate from the $11/2^-$ isomer. The γ-ray intensities are quoted relative to 100 decays of the 190.3-keV γ ray. The order of the isomers in ^{135}Sm is not known.

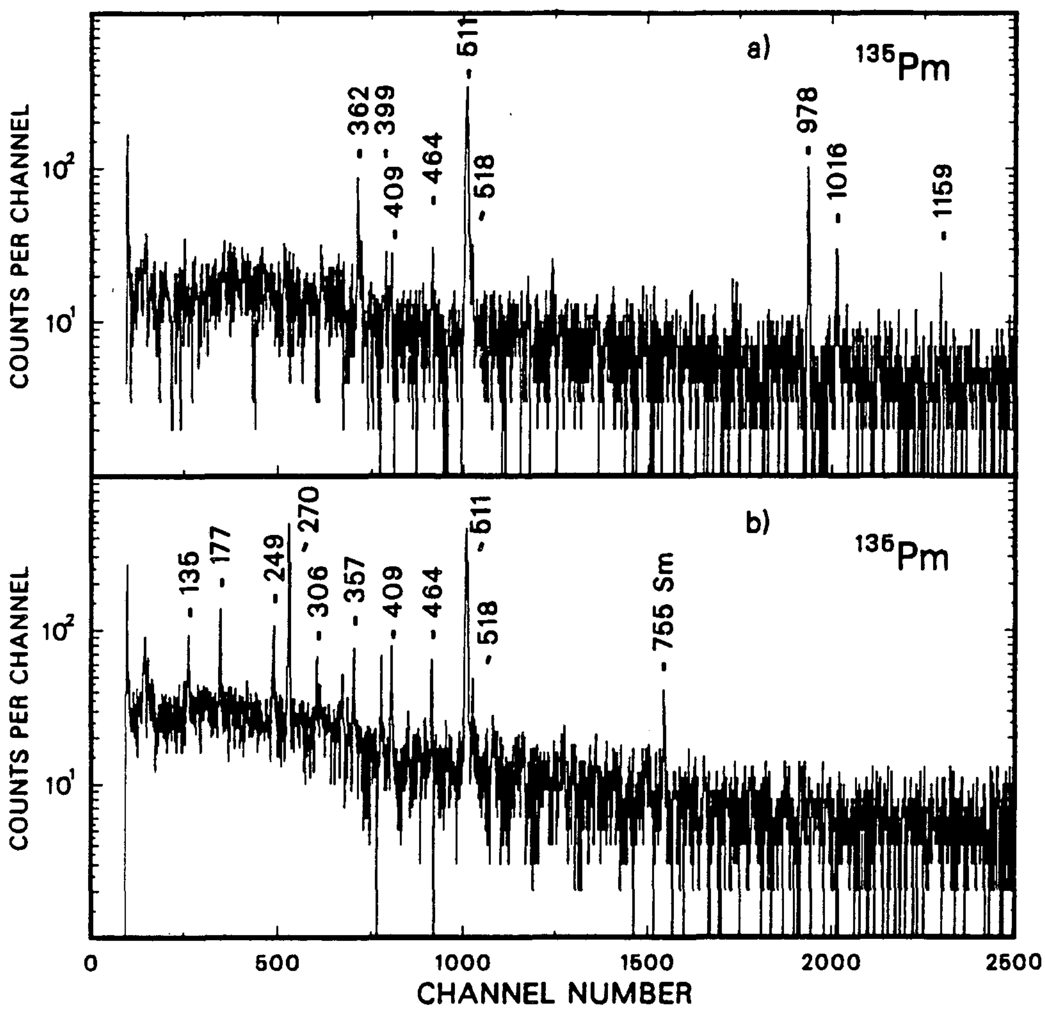

Fig. 6. The 198.8-keV high spin and 128.8-keV low spin gated γ-ray spectra of ^{135}Pm decay measured with the 52.3% Ge detector are presented in a) and b), respectively. Gated background spectra were subtracted. Note that the 409.2-, 463.8- and 518.3-keV γ rays were seen in coincidence with both high- and low-spin gates.

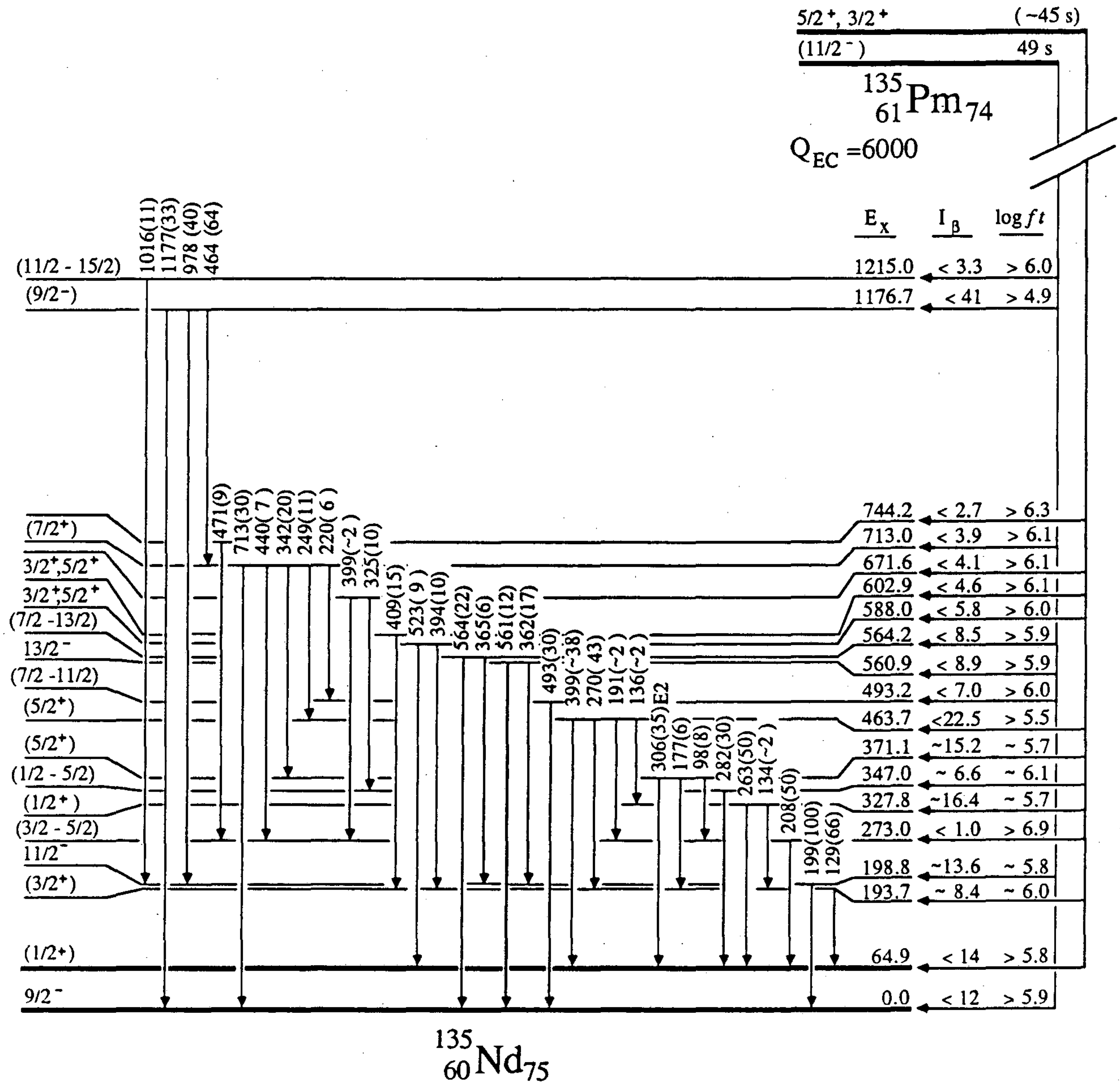

Fig. 7. Tentative decay scheme of ^{135}Pm. The energy and intensity units are the same as in fig. 2. Both the high- and low-spin decays were assumed to represent 50% of the β intensity. The γ intensities are quoted relative to 100 decays of the 198.8-keV γ ray, and average values from 16-s and 40-s tape cycle were used. The order of the isomers in ^{135}Pm is not known.

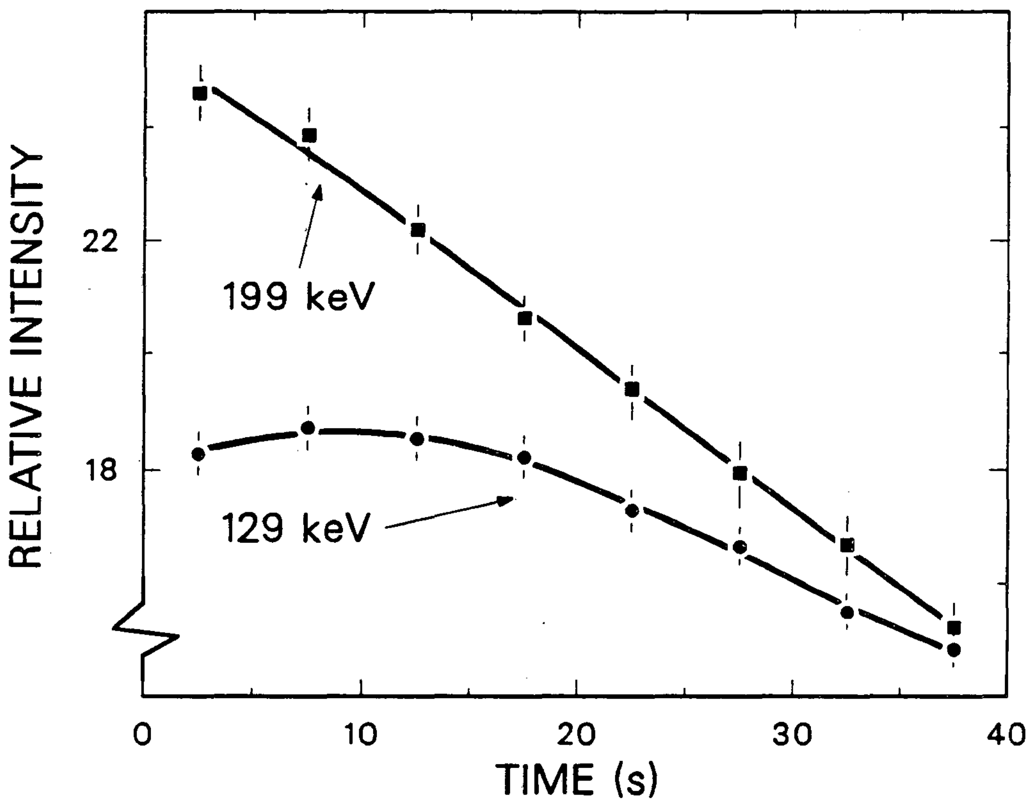

Fig. 8. The intensities of the 129-keV low-spin and the 199-keV high-spin γ transitions in ^{135}Nd as a function of time. The curves are drawn to guide the eye.

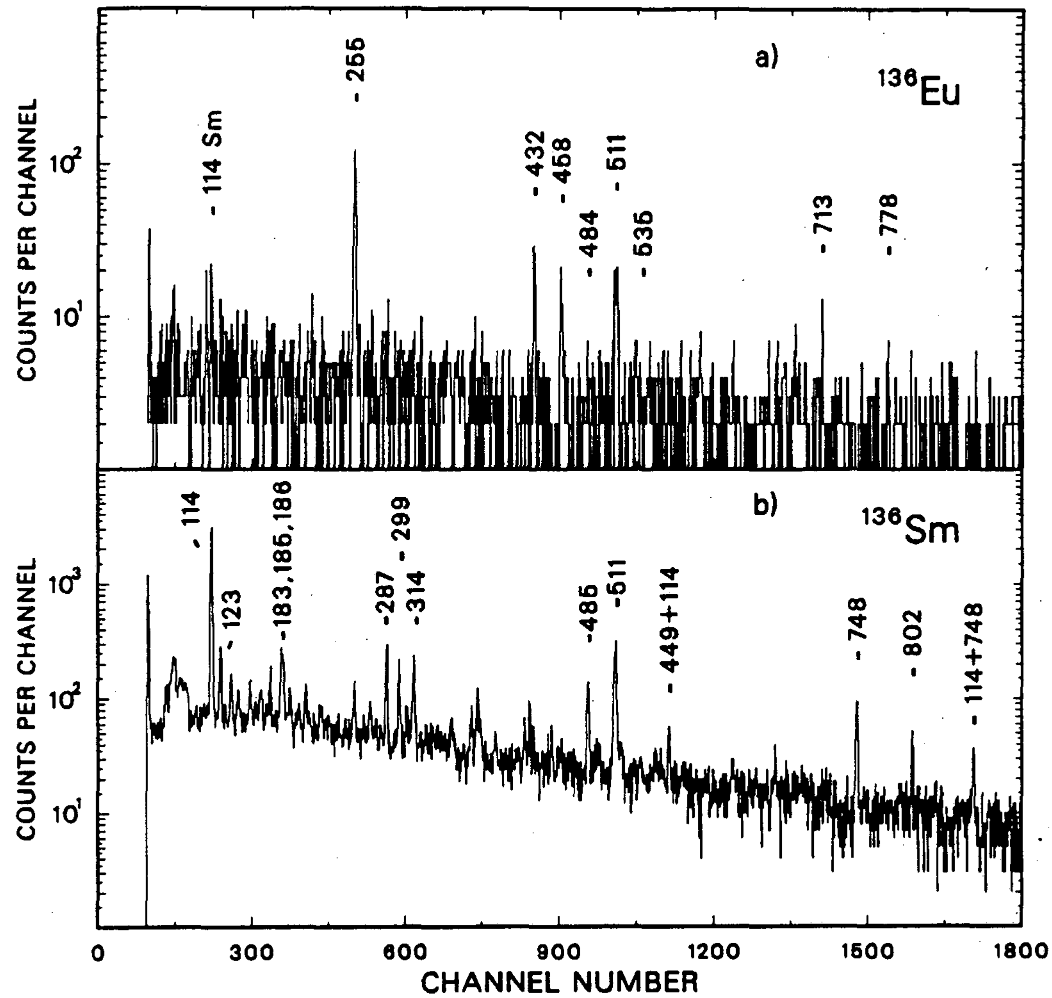

Fig. 9. The Sm and Pm K x-ray coincident γ spectra of ^{136}Eu and ^{136}Sm decay measured with the 52.3% Ge detector are presented in a) and b), respectively; gated background spectra were subtracted.

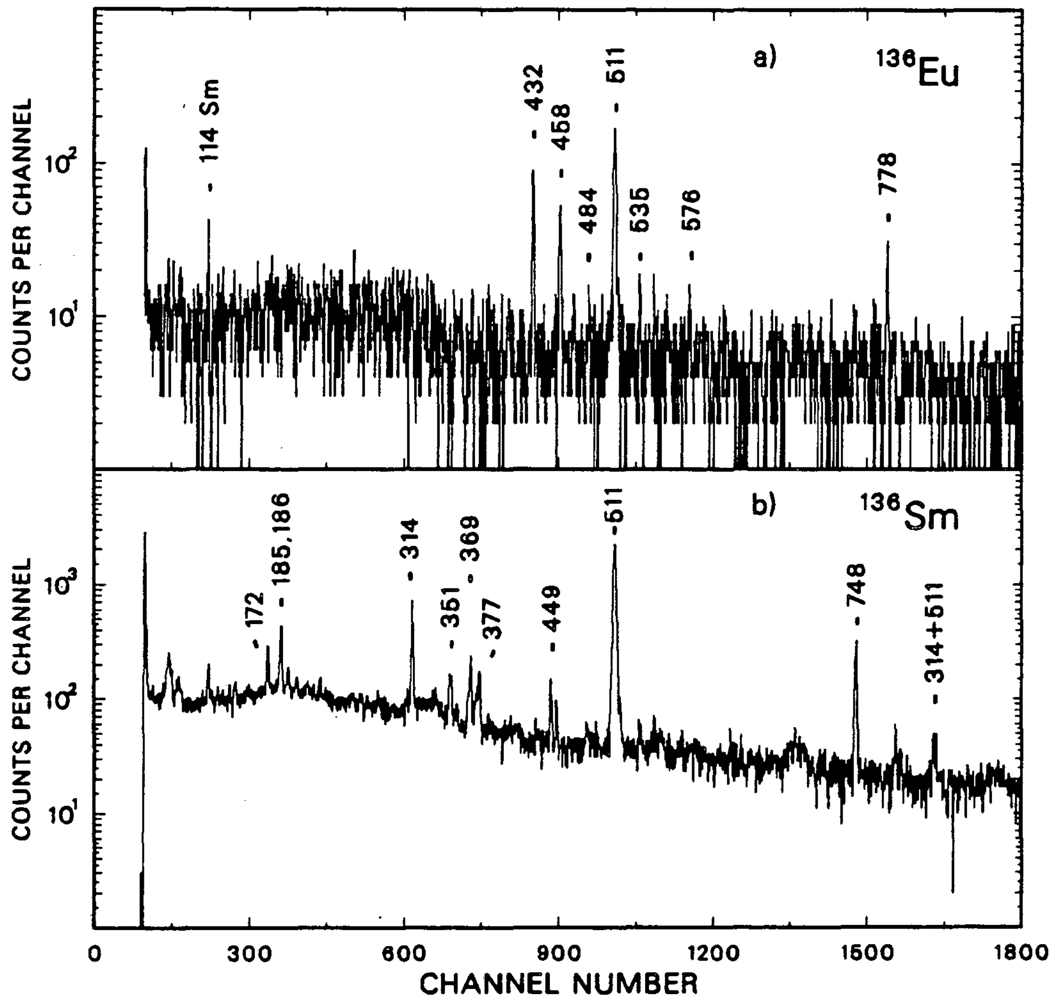

Fig. 10. The ^{136}Eu and ^{136}Sm γ-ray spectra gated by the respective 255-keV and 114-keV transitions are presented in a) and b). Gated background spectra were subtracted.

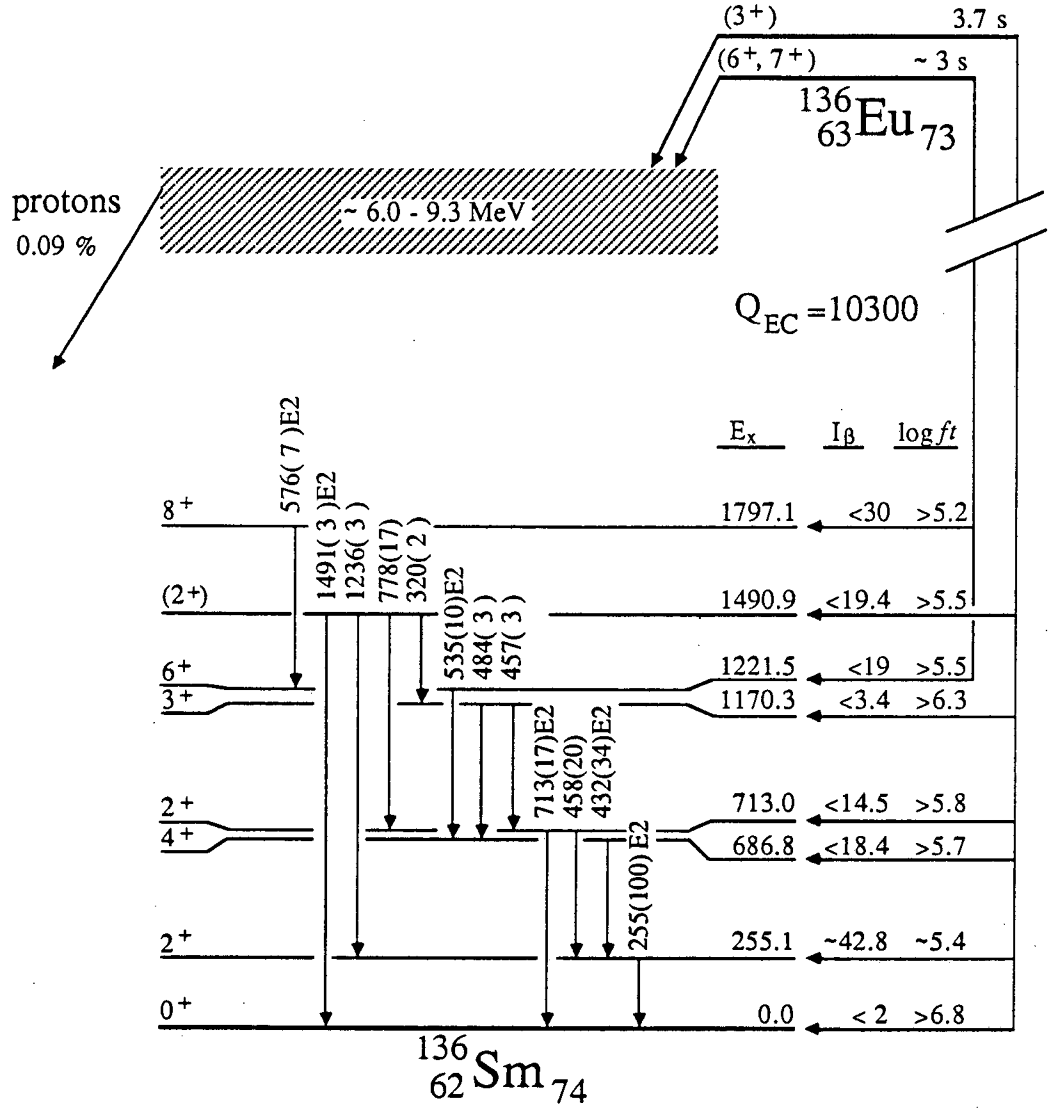

Fig. 11. The decay scheme of ^{136}Eu. The energy and intensity units are the same as in fig. 2. The β-delayed protons are assigned to both low- and high-spin decays. The γ intensities are quoted relative to 100 decays of the 255.1-keV γ ray. The order of the low- and high-spin parent isomers is not known.

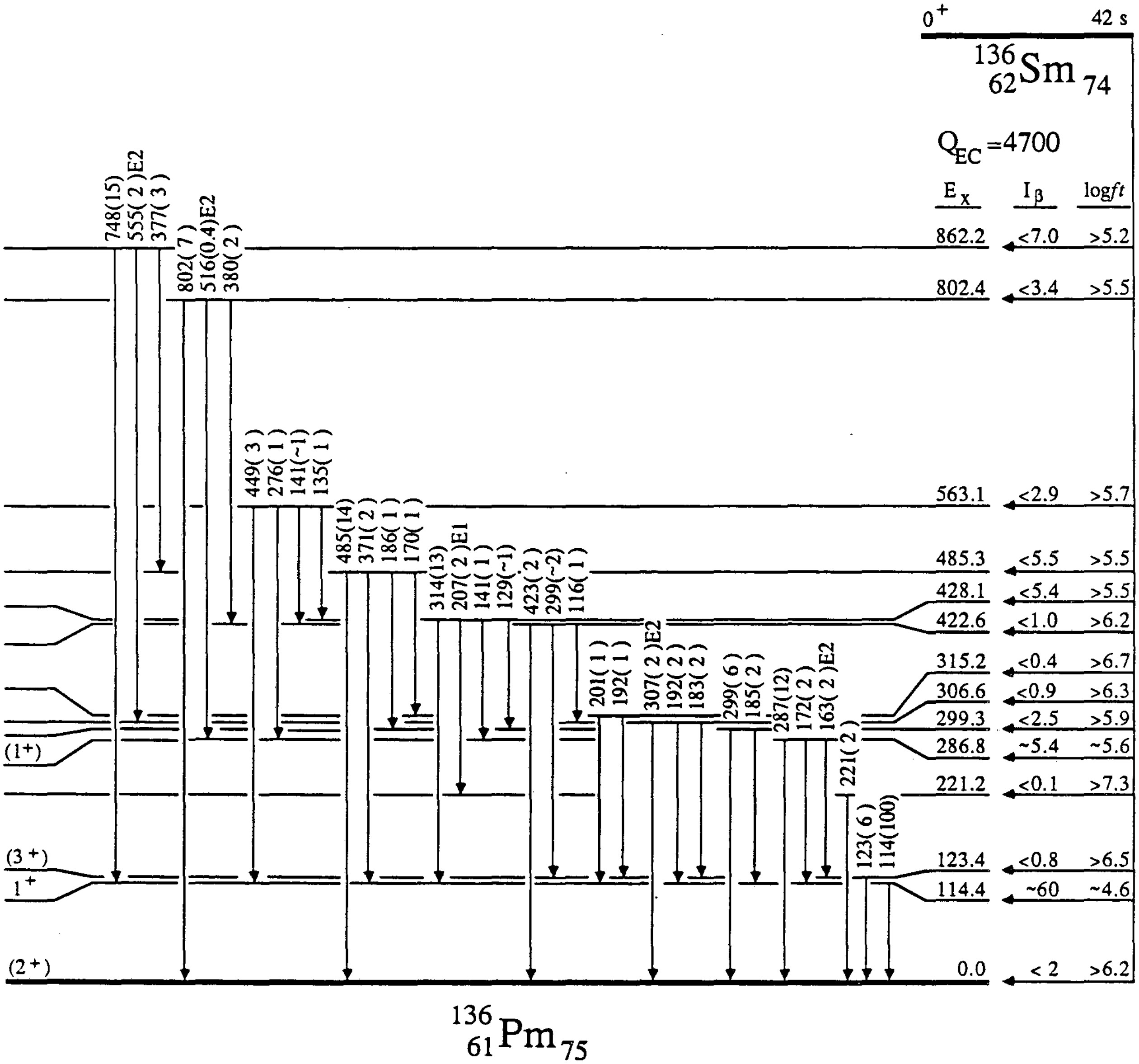

Fig. 12. The decay scheme of ^{136}Sm. The energy and intensity units are the same as in fig. 2. The γ intensities are quoted relative to 100 decays of the 114.4-keV γ ray.

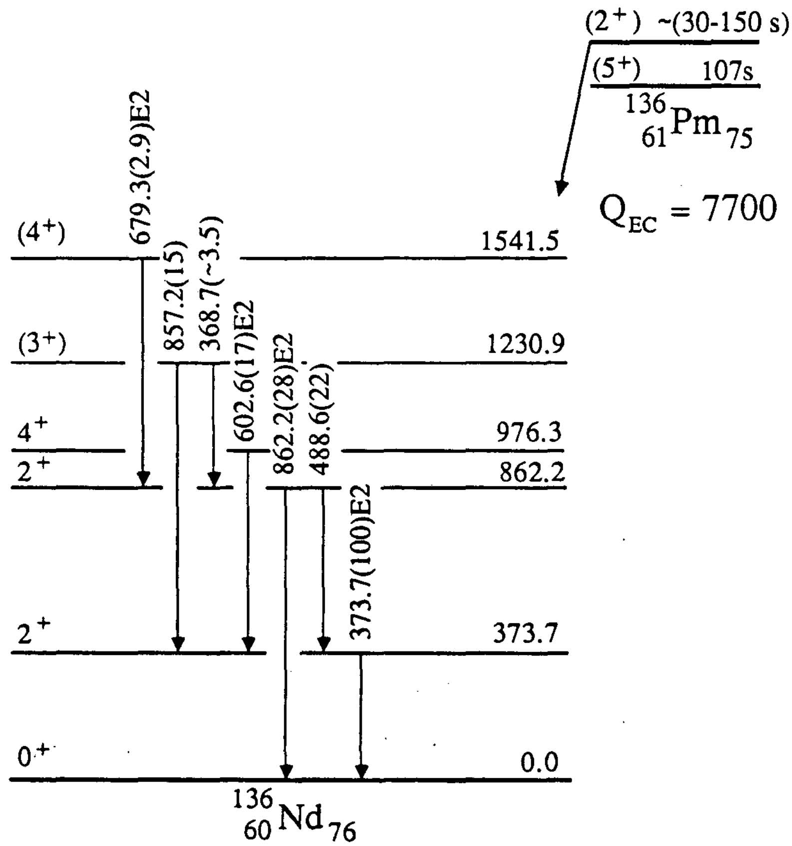

Fig. 13. The decay scheme of the low-spin isomer of ^{136}Pm. The γ-ray intensities are calculated relative to the 373.7-keV $2^+ \rightarrow 0^+$ transition. The order of the isomers is not known.

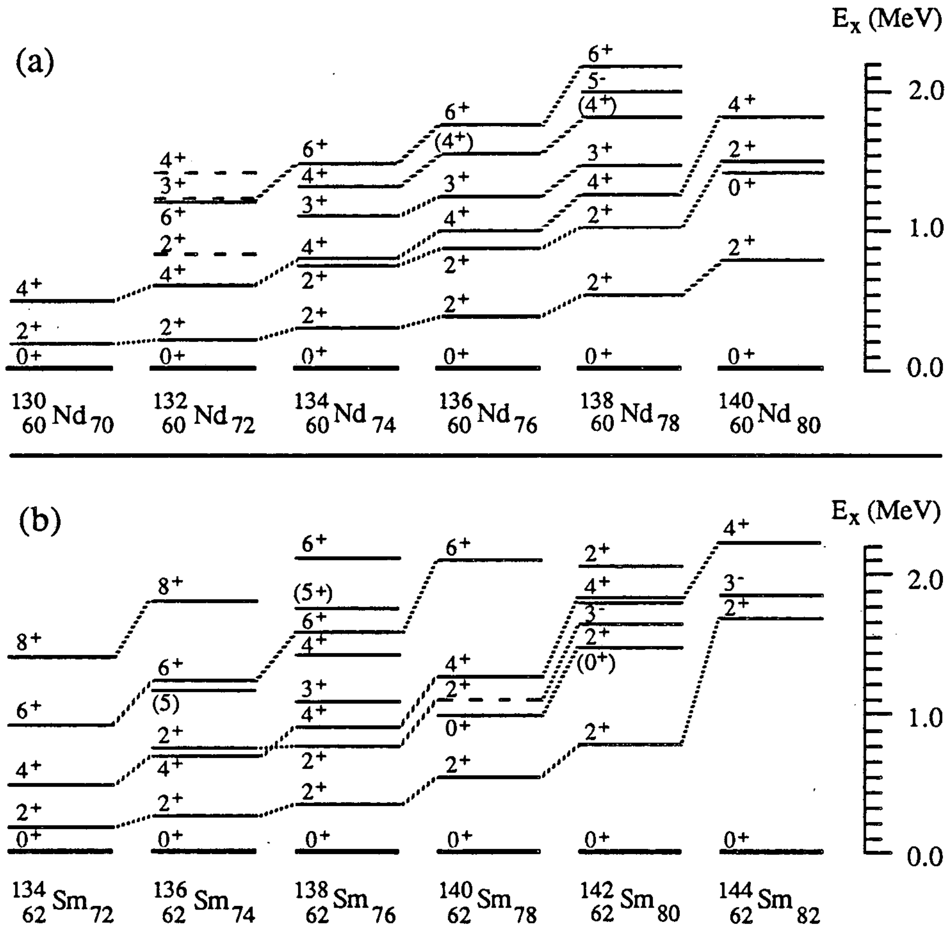

Fig. 14. The level systematics of even-even Nd (a) and Sm (b) isotopes. The level structure information is collected from refs. 5, 8-14 and 20, and from this work.