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1. Introduction

The level structure of the odd-odd nucleus $^{146}_{63}Eu_{83}$ should be understandable from the comparison with the neighbouring odd nuclei with $Z = 63$ or $N = 83$. By the radioactive β^+-decay of the 0^+ ground state of ^{146}Gd mainly the low-spin states of ^{146}Eu are populated. The high angular momentum transfer of the compound nuclear reaction with charged particles offers the possibility of exciting high spin states. Remaev et al. /1/ made use of the $(p, 2n)$ reaction and reported on the existence of an isomeric level with $T_{1/2} = 240 \pm 10\ \mu s$. They found delayed gamma transitions of 240, 280, 360, 390 and 480 keV energy, but no decay scheme could be established. A measurement /2/ of the K/L ratio of the 276 keV transition resulted in the value 6.4 ± 1.5. This value is compatible only with a low multipolarity of this transition, which, therefore, cannot be the isomeric transition.

In order to establish a decay scheme of the 240 μs isomeric state in ^{146}Eu we have carried out in-beam experiments at the U-300 Heavy Ion Cyclotron.

2. Experimental Results

A metallic lanthanum foil of 5.7 mg/cm^2 was irradiated by a carefully focused ^{12}C beam of 81 MeV energy. The prompt and delayed gamma radiation was detected by a Ge(Li) planar detector (1.8 cm^2 x 11 mm) and a 43 cm^3 coaxial detector. The time-energy spectra were recorded with a 2048 channel analyser, two-dimensionally arranged for 8x256, 4x512 or 2x1024 channels. Besides of the natural beam bunching with 237 ns period duration we made use of the millisecond beam pulsing of the cyclotron /3/ . The beam-on time amounts to 1 ms, the beam-off time 2... 4 ms, with a decay time of about 10μs. Each timing cycle was started at the end of a cyclotron pulse, the lengths of the $8x200\mu$s time intervals were determined by a quartz generator of 10μs period duration. In consequence of the analyser dead time of about 80μ s the first time channel does not contain the full amount of events, which has been corrected by an empirical factor.

Fig. 1. shows the obtained prompt gamma spectrum, measured with the 1.8 cm^3 detector, coupled to an ORTEC-180 F preamplifier. The energy resolution amounts to 2 keV. Because the spectrum was measured during the 1 ms beam pulse, besides of prompt gamma lines also lines with ns lifetimes $({}^{147m}Eu)$ are of prominent intensity. The computer calculated gamma ray intensities $(I_{\gamma 2})$ are given in table 1 together with the respective values obtained from two other measurements. The smooth curves in Fig. 1 are computer fits with a Gaussian line shape. The calculations were carried out by use of the program GAMMA /4/ . For the energy calibration the known energy values of ${}^{147m}Eu$ have been used.

The gamma transitions outgoing from the isomeric level in ${}^{146}Eu$ are shown in the delayed spectra of Fig. 2, which were measured after the end of the beam pulse. In table 1 the intensity values of curve $A(I_{\gamma 3})$ are summarized. For the timing conditions of this measurement see the subscript of figure 2. Besides of the strong transitions 275.0, 358.2 and 377.1 keV weak gamma ray lines at 293.7 keV, 317 keV and an unresolved peak at about 136 keV have been observed. For clarification a remeasurement of the low energy part of spectrum A has been performed with better energy resolution. The result of this measurement is depicted by the insert above curve A, but in a somewhat different scale. The 138.8 keV line belongs to a long-lived decay, whereas the 135.5 keV line follows the same decay time as the other delayed transitions.

The decay curves of Fig. 3 have been concluded from the two-dimensional time energy spectra. The half-life values of the weak transitions agree within the experimental errors with that of the strong transitions. The mean value amounts to $T_{1/2} = 235 \pm 3\,\mu s$.

In a special run with the 43 cm^3 Ge(Li) detector transitions of higher energies have been searched for. In the energy range up to ≈ 2MeV no further gamma transitions with about 235 μs half-life have been found.

By means of a NaJ(Tl) scintillation counter and the 43 cm^3 Ge(Li) detector a coincidence measurement between the delayed gamma transitions was performed. The time gate was opened for a time interval of 800 μs, beginning with 500 μs after the end of the beam pulse. In the scintillation counter spectrum windows have been set on the 275 keV peak and on the unresolved peak of the 358 and 377 keV lines. The 275 keV transition was found to be in coincidence with both the 358 and 377 keV transitions.

In order to identify the reaction products prompt and delayed gamma ray spectra have been measured at 5 different energies of the incoming particle, degraded by calibrated aluminium foils.

The time gates were set on the ns-beam-burst and on the time interval between 100 and 200 ns after the burst. Normalizing the intensity values with the intensity of the 229.2 keV transition in ^{147m}Eu ($T_{1/2}$ = 700ns) we obtained the relative excitation functions drawn in Fig. 4, from which we conclude that the found delayed transitions belong to the reaction $^{139}La(^{12}C, 5n)^{146m}Eu$. For comparison also the excitation function of the known 396 keV transition in ^{147m}Eu has been drawn. The excitation functions of the 135.5 keV and the 293.7 keV lines were taken from the prompt spectra, because these lines are very weak in the delayed spectra, but have strong prompt components, whereas the 317 keV transition is very weak in both spectra.

3. Decay Scheme

Based on the result of the coincidence measurement, the energy and intensity balance of the prompt and delayed spectra, the decay scheme of the isomeric state has been concluded. In Fig. 5 also the levels known from the ^{146}Gd decay are drawn.

From the delayed gamma ray spectrum (Fig. 2) we estimated an upper limit of the intensity of delayed KX rays of europium and obtained for the sum of the K-conversion coefficients of all delayed transitions $\alpha_K < 10^{-2}$. Besides of the 275 keV transition also the 358 and 377 keV transitions should, therefore, have low multipole order (EI, E2, MI) and cannot be the isomeric transitions. The not yet assigned 135.5 keV transition is to be ruled out because of its strong prompt component (table I). The energy of the missing isomeric transition is assumed to be smaller than the K binding energy of Eu, i.e. $E_\gamma <$ 50 keV. The single particle estimation shows that the measured half-life corresponds to an M2 character of such a transition.

Some hints on the spin assignments of our level scheme in Fig. 5 gives the β^{+}-decay of ^{146}Gd. From gamma ray, conversion electron and lifetime measurements there is strong evidence for a pure MI cascade connecting the levels 385 keV (1^-), 230.3 keV (2^-), 115.6 keV (3^-) and the ground state (4^-). No transitions known from the ^{146}Gd decay were found in the isomeric deexcitation, which probably goes via high spin levels. Because no branching from the 275 keV level to the 3^- level was observed we conclude that its spin should be $I \geq 5$. Within the experimental error of the K/L ratio [2] the 275 keV transition may also be an E2 transition, and the value $I^\pi = 6^-$ is favoured. The nearly equal intensity of both transitions outgoing from the 652 keV level indicates, that the 294 and the 275 keV levels have probably the same spin. From the multipole order estimated above for the 358 and 377 keV transitions follows a spin value 7 or 8 of the 652 keV level. As is shown in the following section, for the isomeric state $I^\pi = 9^+$ is to be expected. The assumed M2 character of the isomeric transition favours $I^\pi = 7^-$ for the 652 keV level.

4. Discussion

A comparison with the neighbouring odd A nuclei with $Z = 63$ or $N = 83$ gives some hints on the nature of the $^{146}_{63}Eu_{83}$ levels. In Fig. 6 the experimentally observed excitation energies of one-quasiparticle proton states in the odd A europium nuclei ($Z = 63$) are compiled. Interpolating between the neutron numbers 82 and 84 we obtain for $N = 83$ the mean values: 0 keV ($d_{5/2}$), 280 keV ($g_{7/2}$) and 670 keV ($h_{11/2}$). In the $N = 83$ isotones $^{145}_{62}Sm_{83}$ and $^{147}_{64}Gd_{83}$ the ground states are characterized by the $p_{3/2}$ neutron configuration and the first excited states at 894 and 1153 keV, respectively, by the $f_{7/2}$ neutron state. For $Z = 63$ the mean value of the $p_{3/2}$ state amounts to 1025 keV. We assume, that in $^{146}_{63}Eu_{83}$ the lowest lying states are formed by the neutron coupled to the proton states $(d_{5/2})^{-1}$, $(g_{7/2})^{-1}$, $(h_{11/2})^{1}$. The energy differences between the centres of gravity of these two-quasiparticle multiplets are nearly equal to the above-mentioned mean values of the odd-proton excitation energies. Not taking into account differences of the multiplet splitting due to differences of the wave functions the centres of gravity and the lowest lying multiplet states have nearly the same energy distances from each other.On the left-hand side of Fig.5 the expected energy values of the lowest-lying states of the two-quasiparticle multiplets are drawn together with the spin values calculated from the Brennan-Bernstein coupling rules /5/ .

As is known from the even Tb isotopes (A = 148, 150, 152), long-lived isomeric states are formed by the $\pi(h_{11/2})^1 \nu(f_{7/2})^1$ configuration, which, therefore /6/ , is assumed to form also the isomeric state in ^{146}Eu . The expected energy of the lowest lying state of this configuration agrees well with the experimental data.

Very probably one of the proposed 6^- levels together with the levels populated in the ^{146}Gd decay are members of the broken $\pi(d_{5/2})^{-1}$ $\nu(f_{7/2})^1$ multiplet, whereas the other 6^- level and the 7^- level at 652 keV belong to the $(g_{7/2})^{-1}(f_{7/2})^1$configuration. This is confirmed by the following considerations: in pure two-quasiparticle multiplets of different configuration the energy values of the odd and even spin states lay on two separated curves /7/ , as shown in Fig. 7. If the multiplet splitting is preferentially caused by the Wigner forces the $E - I$ diagram is inverted if we go over from a particle-particle (hole-hole) configuration to a particle-hole configuration, because the sign of the Wigner forces is changed.

Drawing the $E - I$ diagram of the ^{146}Eu levels, we get the same course as for a particle-hole configuration, which is in accordance with the assumed level structure.

Admixtures of other close lying configurations may cause dislocation and deformation of these curves. Especially the odd spin states seem to disagree with the theoretically predicted behaviour, as shown by the neighbouring isotone ^{142}Pr /8/ . A slight shift of the even I curve may cause the discrepancy between the experimentally observed ground state spin 4 and the value 5 deduced from the Brennan-Bernstein rule.

References

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Table I. Relative gamma intensities

E_γ /keV	$I_{\gamma 1}$	$I_{\gamma 2}$	$I_{\gamma 3}$
135.5 ± 0.1	54 ± 3	25.8 ± 2	1.95 ± 0.2
275.0 ± 0.05	100	100	100
293.7 ± 0.1	116 ± 6	50 ± 3	1.9 ± 0.2
317.0 ± 0.8	–	≤5	0.99 ± 0.1
358.2 ± 0.1	–	43 ± 3	49 ± 3
377.0 ± 0.1	47 ± 4	40 ± 3	44 ± 3

The intensity values have been calculated for $I_{\gamma 1}$ from the prompt spectrum, when the time gate was set on a single ns beam burst, $I_{\gamma 2}$ from the prompt spectrum in Fig. I, measured during the I ms pulse, $I_{\gamma 3}$ from the delayed spectrum in Fig. 2.

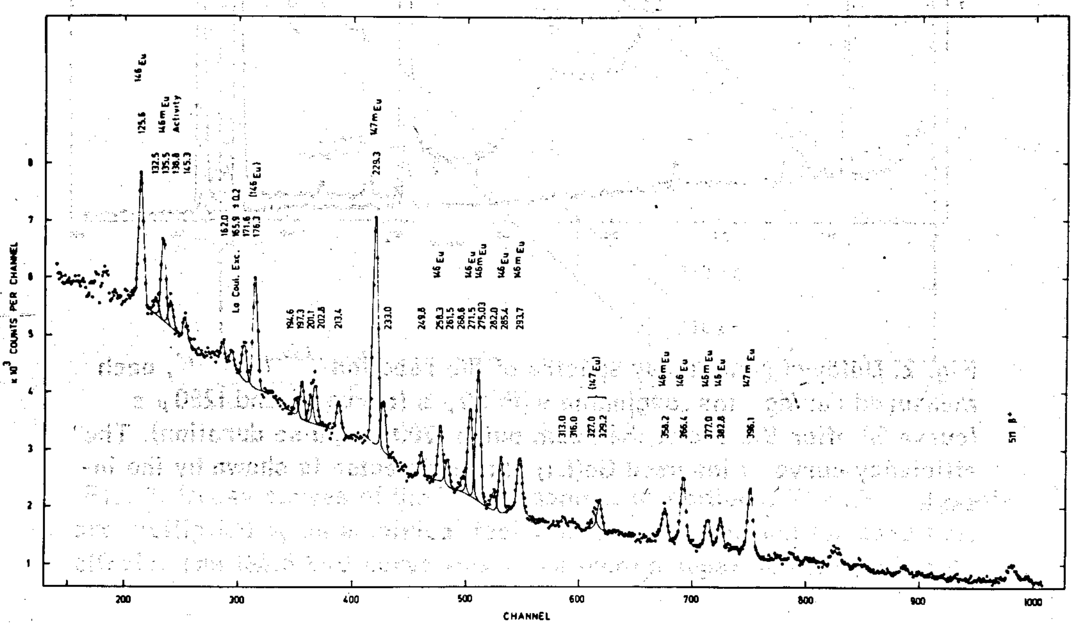

Fig. I. Gamma ray spectrum of the reaction $^{139}La + {}^{12}C$, measured during the I ms beam pulse.

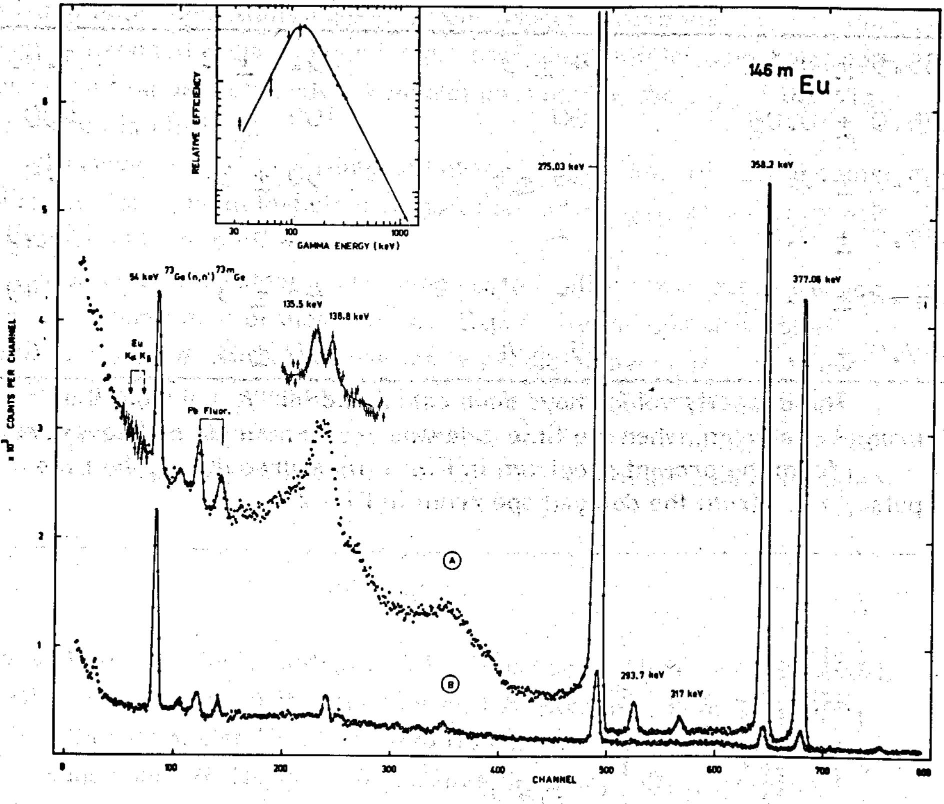

Fig. 2. Delayed gamma ray spectra of the reaction $^{139}La + ^{12}C$, each measured during 1 ms, beginning with 30 μ s (curve A) and 1280 μ s (curve B) after the end of the beam pulse (700 μ s pulse duration). The efficiency curve of the used Ge(Li) planar detector is shown by the insert.

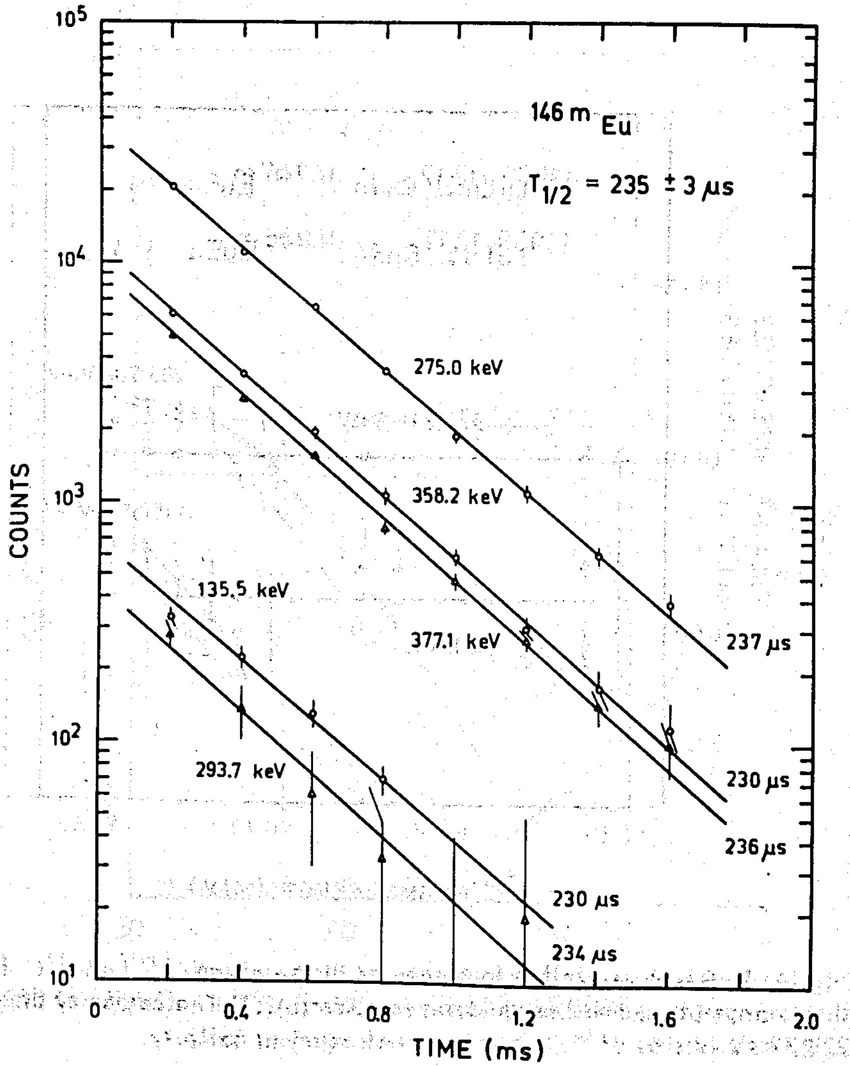

Fig. 3. Decay curves of the ^{146m}Eu gamma transitions. The 200 μs points are multiplied by an empirical factor in order to correct for dead time effects. The 135.5 keV curve was taken from a separate measurement.

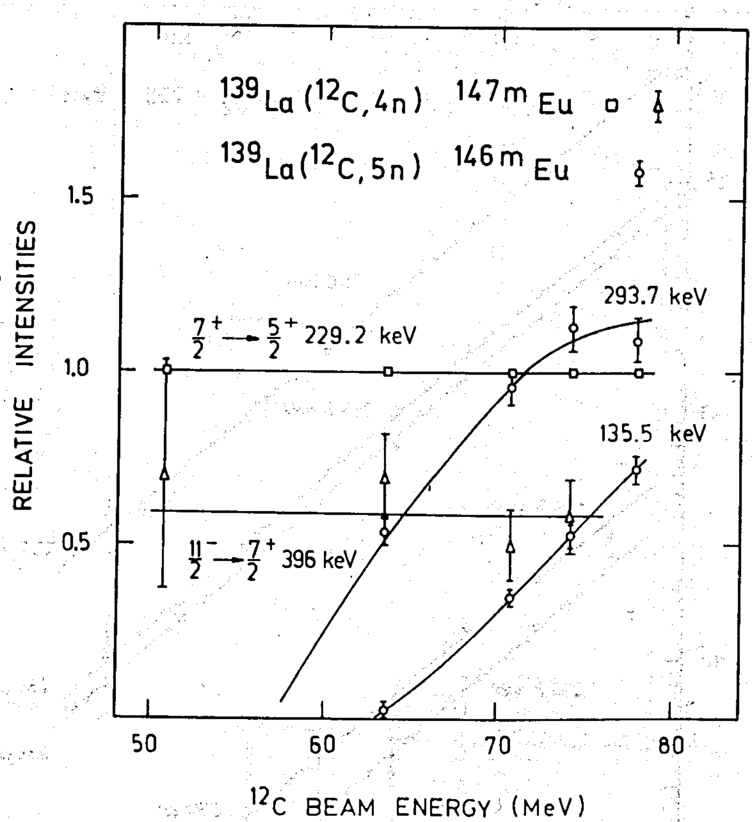

Fig. 4a. Relative excitation functions of the reaction $^{139}La + ^{12}C$ from the prompt (a) and the ns-delayed spectra (b). The intensity of the 229.3 keV line of ^{147m}Eu has been set equal to unity.

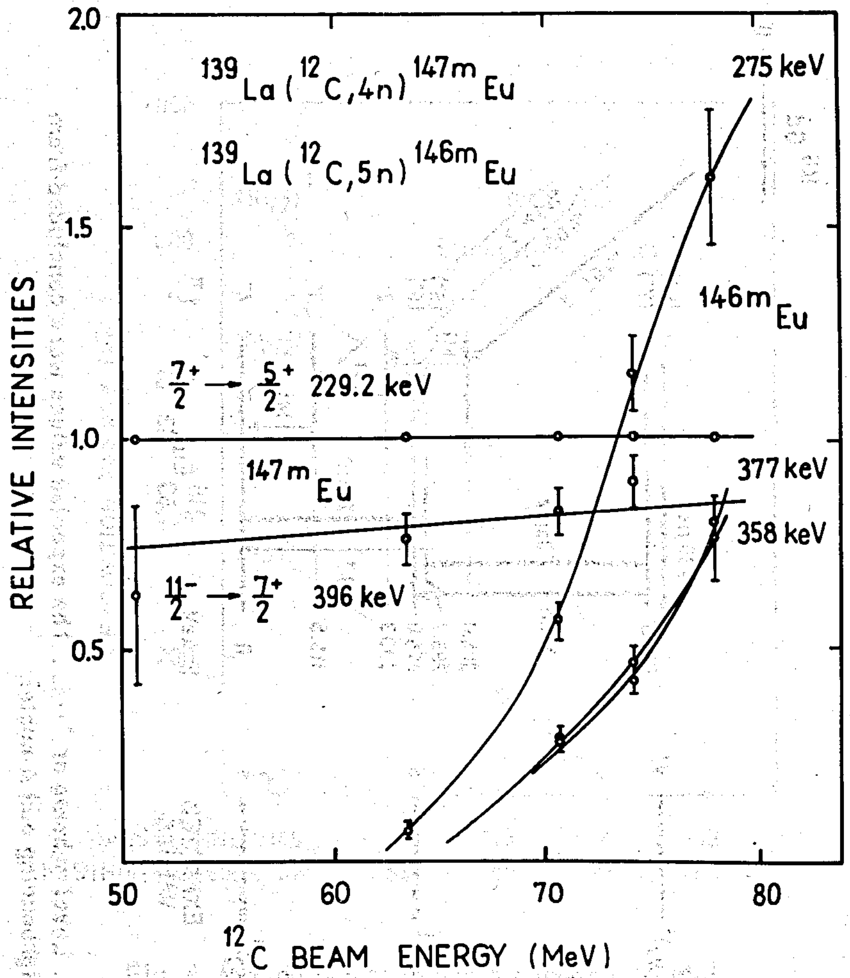
2.0
1.5
1.0
0.5
$^{139}La(^{12}C,4n)^{147m}Eu$
$^{139}La(^{12}C,5n)^{146m}Eu$
275 keV
^{146m}Eu
$\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$ 229.2 keV
^{147m}Eu
377 keV
358 keV
$\frac{11}{2}^- \rightarrow \frac{7}{2}^+$ 396 keV
RELATIVE INTENSITIES
50
60
70
80
^{12}C BEAM ENERGY (MeV)

Fig. 4b.

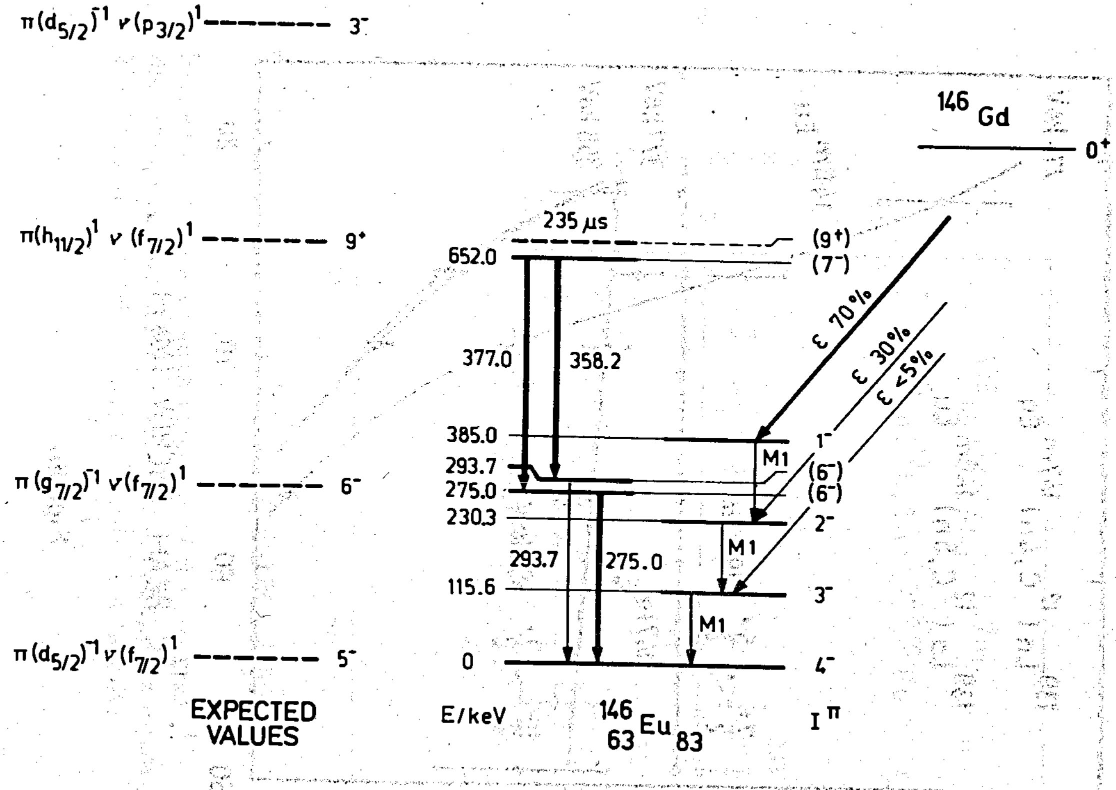

Fig. 5. Level scheme of ^{146}Eu. The expected values were concluded from the neighbouring odd A nuclei.

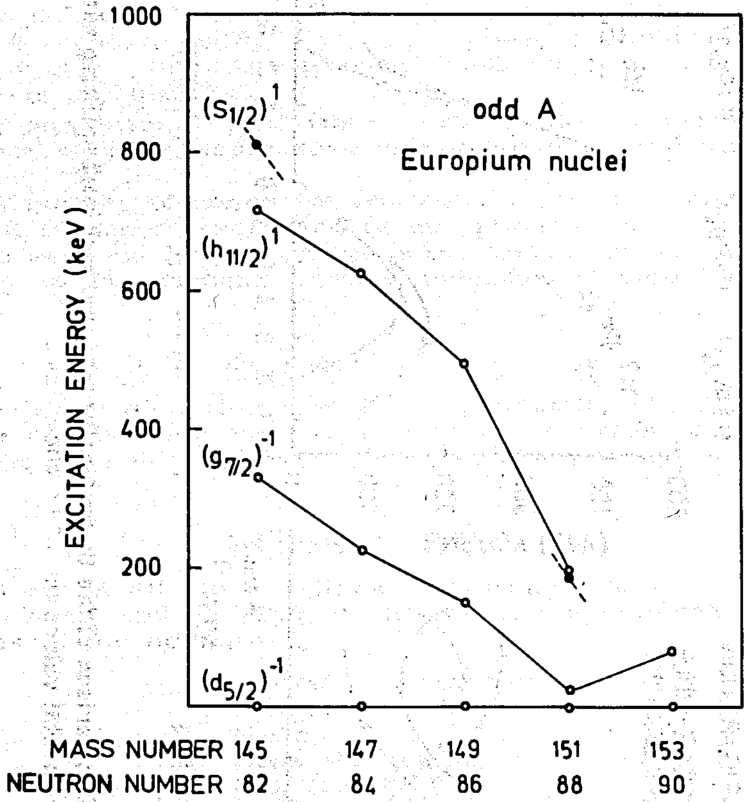

Fig. 6. Proton levels in odd A europium nuclei.

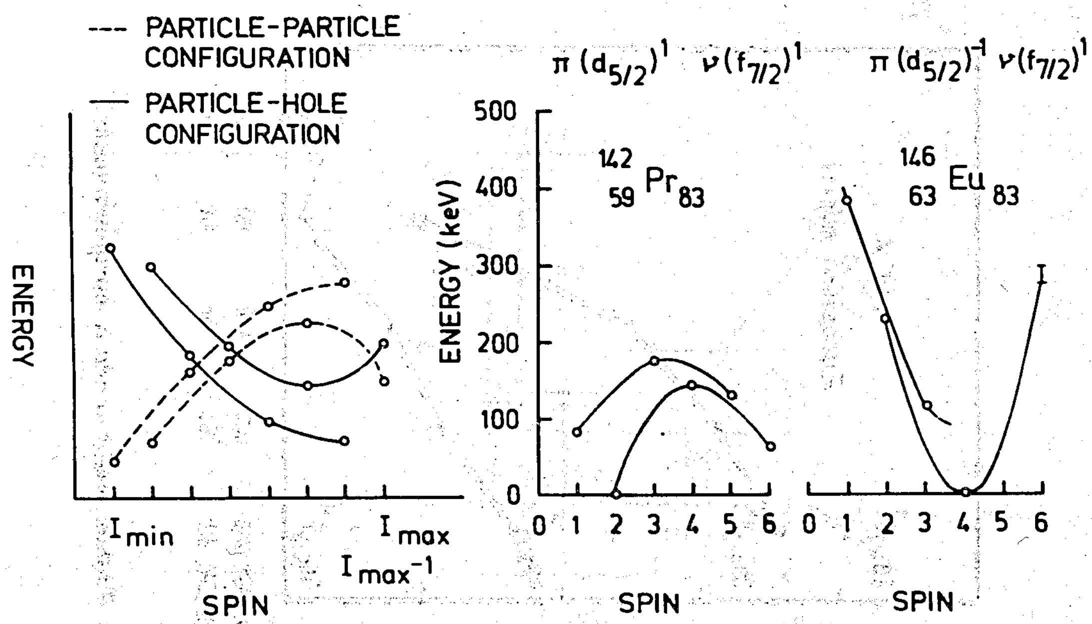

Fig. 7. Comparison of the theoretically expected multiplet splitting with the experimental values in ^{142}Pr and ^{146}Eu .