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Measurement of the Circular γ-Polarisation after n-Capture in ^{141}Ce, ^{144}Nd and ^{140}La using Ge(Li)-Detectors*)

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Abstract

By applying the circular polarization technique spins of nuclear levels were investigated. For the 0.662 MeV level of ^{141}Ce the spin $3/2^-$ was deduced. The Spin of the 1.56 MeV and 1.31 MeV levels of ^{144}Nd are confirmed $I^\pi = 2^+$, 3^+ (or 5^+) and 4^+ (or 3^+). Further the spins for the 0.32 MeV and 0.064 MeV states in ^{140}La were determined $I^\pi = 3^-$ (or 4^-) and 3^- or 4^-, respectively.

Durch Beobachtung der zirkularen Polarisation einer γ-Strahlung nach Einfang polarisierter Neutronen wurden die Spins einiger Kernzustände bestimmt. Für das 0.662 MeV Niveau von ^{144}Ce wurde der Spin $3/2^-$ festgelegt. Der Spin der Niveaus bei 1.56 MeV und 1.31 MeV in ^{144}Nd konnte auf $I^\pi = 2^+$, 3^+ (oder 5^+) bzw. 4^+ (oder 3^+) eingeschränkt werden. Für ^{140}La wurden die Spins der Niveaus bei 0.32 MeV und 0.064 MeV zu $I^\pi = 3^-$ (oder 4^-) bzw. 3^- oder 4^- bestimmt.

1. Introduction

The investigation of the circular polarization of neutron-capture γ-rays is an elaborated technique in nuclear spectroscopy for the determination of spins and mixing ratios. For this method polarized thermal neutron beams are necessary. When the neutrons are captured in nuclei the polarization is transferred to the compound-state. In the case of thermal neutrons an orientation of first degree arises and the γ-radiation from the decay of the compound-state is circularly polarized. The polarization P_c is given by

$$P_c = P_n R \cos \theta, \qquad (1)$$

where P_n is the polarization of the neutrons and θ is the angle between the direction of the neutron spin and γ-emission. The factor R is determined by the properties of the nuclear levels, i.e. by the spin of the target nucleus I_i, the compound-state I_c and final state I_f, and by the mixing ratio of the radiation. For pure dipole radiations the following relation exists[1)]

$$R = \frac{2(I_c - I_i)}{2I_i + 1} \quad \frac{2 + I_c(I_c+1) - I_f(I_f+1)}{2} \qquad (2)$$

By measurement of R information about the spins can be obtained. In older experiments NaI-detectors were used, which suffer from poor energy resolution. Recently by using large Ge(Li)-detectors this technique could be extended to a variety of γ-transitions, which could not be resolved by NaI-counters [2,3)]. However, the efficiency of even large Ge(Li)-detectors is one order of magnitude lower compared with a (7.5 x 7.5 cm) NaI-crystal, which is commonly used. Because of the poor transmission of the polarimeters and the low detector efficiency measuring times of several weeks are necessary. An approvement may be achieved by more intensive polarized neutron beams, which are now available [4)].

2. Experimental arrangement

As a thermal neutron source the Karlsruhe 44 MW reactor FR2 was used. A collimated neutron beam was polarized by total reflection from a magnetized mirror (94 % Co - 6 % Fe). The intensity was $6 \cdot 10^{-6}$ neutrons $\cdot$ s^{-1} with a polarization of 65 %. A more detailed description of the beam can be found in preceeding publications [5)].

The capture γ-rays were analyzed by two Ge(Li)-detectors (Philips), which were installed parallel and antiparallel to the direction of the neutron spin (fig. 1). The effective volume of the crystals was 42- and 56 cm^3, respectively. Magnetized iron zylinders of about 10 cm length, which were placed between the target and the Ge(Li)-detectors, served as Compton polarimeters [6)]. The transmission (about 5 %) for γ-quanta depends on the degree of circular polarization. The analyzing efficiency, i.e. the relative counting rate difference between total right hand and left hand polarization is about 6 % for energies between 5-8 MeV.

The neutron spin was reversed every 100 s and the γ-spectra were accumulated separately for the two counters and neutron spin directions. Two multichannel analyzers (1024 (Inter-technique) and 400 (TMC) channels) were devided in two halves each. Commercial preamplifiers and biased amplifiers (Canberra) were used. The system resolution was 16 KeV for 5.54 MeV (S(n,γ)) radiation. Probably this value could be lowered by a better matching of the electronic parts. A typical spectrum is shown in fig. 2.

The circular polarization of a γ-transition was determined for each detector by relative counting rate difference

$$E = 2\ (N(o^{\circ})-N(180^{\circ}))/(N(0^{\circ})+(180^{\circ})) \qquad (3)$$

where $N(0^{\circ})$ and $N(180^{\circ})$ is the counting rate for 0° and 180° between the direction of neutron spin and γ-detection.

For determining the factor R from the measurement of E several corrections have to be applied:

(i) By a gauge measurement the neutron polarization, the analyzing efficiency of the polarimeters and the influence of the finite solid angles have to be determined. This was done by investigating the 5.54 MeV transition in $^{32}S(n,\gamma)$. Here the factor R=0.5 can be calculated. By measurement of E the gauge factor a = 30.0 ± 1.5 was determined (see eq. (4)). For obtaining a high accuracy measurements with Ge(Li) - and NaI-detectors were combined. Within the experimental error both measurements yielded the same result:

a=29±5 with Ge(Li)- and a=30,5 ± 1,6 with NaI-detectors.

(ii) The background has to be respected by a factor α, which is the ratio of background to total counting rate within a line.

(iii) In some cases the background may be polarized especially when lines are investigated in the presence of γ-rays of higher energy. The polarization E_1 of the background is not very strong dependent on energy, and the polarization may be integrated over a great energy interval ($\sim$0.5 MeV). The size of E_1 has been determined experimentally in the neighbourhood of the relevant peaks.

With theses corrections the factor R is given by

$$R = \frac{(E-\alpha E_1)\ a}{(1-\alpha)} \tag{4}$$

3. Results and Discussion

Natural targets of S, CeO_2, Nd_2O_3 and La_2O_3 were exposed to the beam. The measuring time for each element under investigation was about four weeks. For the evaluation of E the full peak, first and double escape peaks were used. The experimental results are shown in table 1.

3.1 The reaction $^{140}Ce(n,\gamma)$

The ground-state of ^{140}Ce has spin 0^+ and by S-neutron capture a compound-state with spin $1/2^+$ is formed. In this work we have measured the circular polarization of the 4.77 MeV γ-ray from the compound state to the 0.662 MeV level (fig. 3). The spin of this state is unknown so far. One may assume, however, that the spin of this level is $1/2^-$ or $3/2^-$, because the 4.77 MeV transition is probably a E 1 radiation. This may be concluded because the relative intensity of this line is rather high. The calculated values for R for the two possible final state spins are shown in table 2. By comparison with the experimental result for R the spin of the 0.662 MeV level can be determined to $3/2^-$.

3.2 The reaction $^{143}Nd(n,\gamma)$

Spins for energy levels of the nucleus ^{144}Nd have been studied by angular correlation method [7] and by investigation of the γ-radiation from polarized nuclei [8]. In the present work the circular polarization technique was applied. Due to low counting rates, it was not possible to obtain the same accuracy. The agreement between the different experiments is satisfactory.

In the neutron capture γ-spectrum two intensive γ-lines are visible at 6.25 MeV and 6.5 MeV, which were investigated (fig. 5 and 6). The results for the polarization measurements are shown in table 1. Since the spin of the target nucleus is $7/2^-$ the compound-state has spin 3^- or 4^- or a noninterfering superposition of both. Assuming that the radiations are E1 the possible spins for the energy levels after γ-emission are shown in table 3. By comparison of the calculated values for R with the experiment we obtain the following possible values for the spins: The 1.56 MeV level of ^{144}Nd has spin 2^+, 3^+ or 5^+ and the 1.31 MeV level has spin 3^+ or 4^+. By assuming that the compoundstate has spin 3^- as has been shown in ref. (8) these values reduces to spin 2^+ or 3^+ for the 1.56 MeV level and to spin 4^+ for the 1.31 MeV state. As shown in table 4 agreement with other measurements exist.

3.3 The reaction $^{139}La(n,\gamma)$

By capture of thermal neutrons in ^{139}La two strong γ-transitions occure, leading to the 0.064 MeV and 0.32 MeV levels (fig. 7). It may be assumed that these radiations have E1 character. The spin of the target nucleus is $7/2^+$ and thus the compound-state spin is 3^+ or 4^+. Thus the 0.064- and 0.32 MeV levels may have spin 2^-, 3^-, 4^- or 5^-. Table 3 shows the calculated R-values for the various combinations. By comparison with the measurements the following decision about spins in ^{140}La can be made: The spin of the 0.064 MeV level is 3^- or 4^-. For the 0.32 MeV level the spin 3^- is probable. Due to poor statistics, the spin 4^- can be excluded only with a probability of 13 %.

To clarify the situation, information about the spin of the compoundstate is desirable. In a previous paper it was shown that the spin or the incoherent superposition of the two possible spins for the compound-state can be determined by measurement of the average circular γ-polarization [9]. The measurement of the polarization averaged over the γ-spectrum between 1.6 and 5.5 MeV yielded $\bar{R} = 0.08 \pm 0.02$. The theoretical value for R depends on the spin of the compound-state and on the "spin cut-off factor" σ. The cut-off parameter is given by a statistical theory:

$$\sigma = \frac{IT}{h^2} \tag{5}$$

Here I is the moment of inertia and T is the nuclear temperature. The dependence of R on the parameter is shown in fig. 9. Unfortunately the parameter is unknown. For most nuclei it has been found $3 \lesssim \sigma \lesssim 4$. Thus it may be concluded from fig. 9 that over 70 % of the compound-state has spin 4. This result is in agreement with the circular polarization measurement of the 4.84 MeV transition, which indicated 4^+ for the compound-state and 3^- for the 0.32 MeV level.

The authors would like to thank Prof. Dr. H. Schopper for his interest in this work. We are also indebted to the operator crew of the reactor FR2.

Table 1:

Experimental results for the measurement of the circular polarization of neutron capture γ-rays.

γ-transition	final state	$Ex10^3$	E_1x10^3	α	R
$^{32}S(n,\gamma)$		test experiment		a = 30.0 ± 1.5	
$^{140}Ce(n,\gamma)$ 4.77 MeV	^{141}Ce 0.66 MeV	- 5.5 ± 2.8	- 1.7 ± 0.7	0.84	- 0.8 ± 0.7
$^{143}Nd(n,\gamma)$ 6.5 MeV	^{144}Nd 1.31 MeV	+ 5.2 ± 1.9	- 1.2 ± 0.7	0.58	0.42 ±0.18
" 6.25 MeV	" 1.56 MeV	- 2.9 ± 2.0		0.75	- 0.24± 0.32
$^{139}La(n,\gamma)$ 4.84 MeV	^{140}La 0.32 MeV	+ 9.1 ± 1.6	2.0 ± 0.6	0.74	0.88± 0.28
" 5.10 MeV	" 0.064MeV	+ 4.7 ± 1.6		0.7	0.33± 0.22
$^{139}La(n,\gamma)$ 1.6-5.5 MeV		2.0 ± 0.3		0.18	0.08± 0.02

Table 2: Calculated R-values for the possible spins of the 0.66 MeV level of ^{141}Ce

Spin I_f	$1/2^-$	$3/2^-$	
R	1	-1/2	Experiment R = -0.8 ± 0.7

Table 3: Calculated R-values for the possible spins of the 1.56 MeV, 1.31 MeV levels in ^{144}Nd, and 0.32 MeV, 0.064 MeV levels in ^{140}La.

Spin of compound-state I_c	Spin of final state I_f: 2	3	4	5	Experiment R	
3	-1/2	-1/8	3/8	noE1	-0.24 ± 0.32	1.56 MeV ^{144}Nd
					0.42 ± 0.18	1.31 " ^{144}Nd
4	noE1	5/8	1/8	-1/2	0.88 ± 0.28	0.32 " ^{140}La
					0.33 ± 0.22	0.064" ^{140}La

Table 4: Conclusion about spins by measurement of the circular polarization of γ-rays

Level	Conclusion about spin	comparison with previous works
^{141}Ce 0.66 MeV	$3/2^-$	-
^{144}Nd 1.56 MeV	$2^+, 3^+$ (or 5^+)	2^+
^{144}Nd 1.31 MeV	4^+ (or 3^+)	4^+
^{140}La 0.32 MeV	3^- (or 4^-)	-
^{140}La 0.064MeV	3^- or 4^-	-

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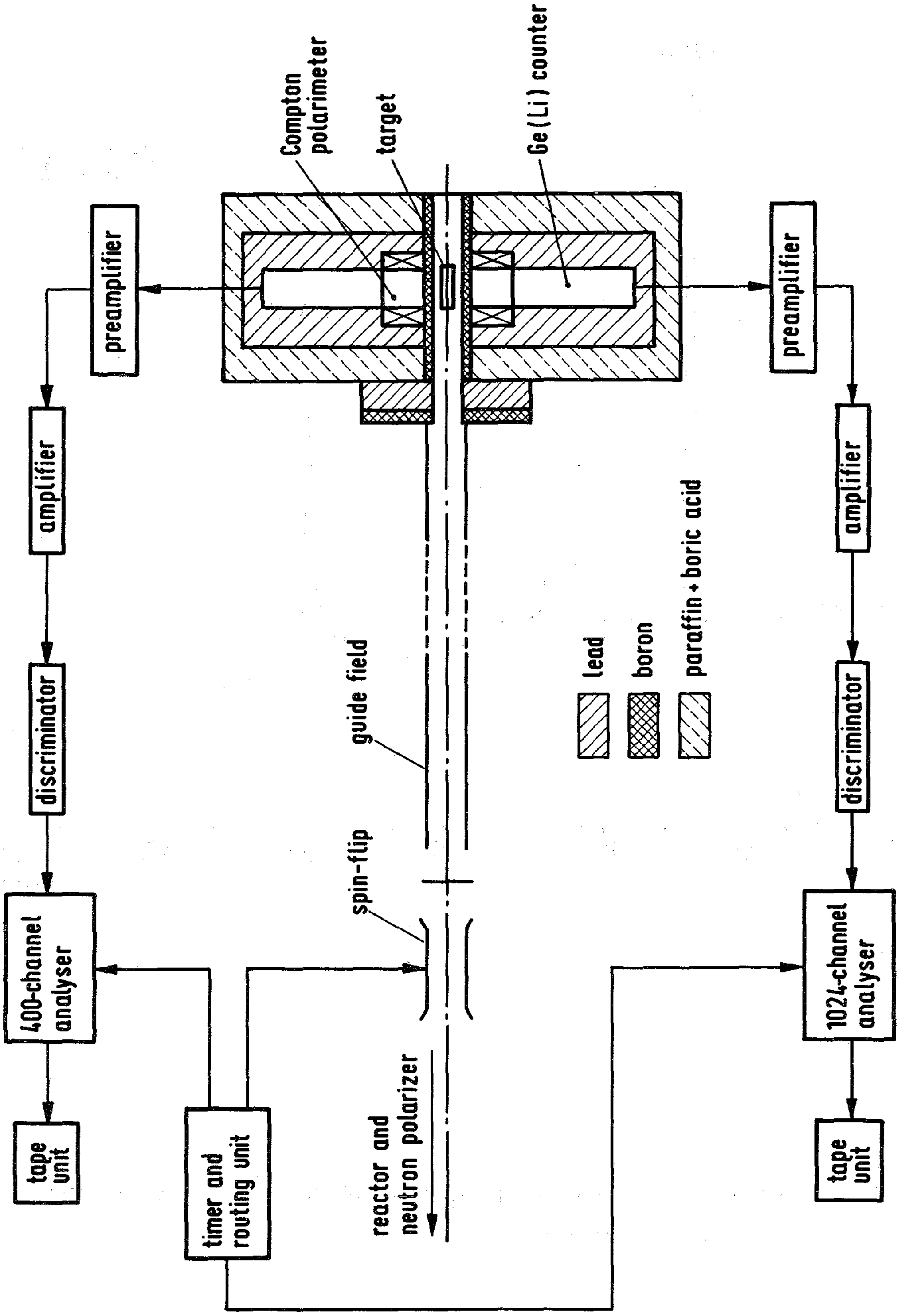

Fig. 1: Experimental arrangement for measuring the circular polarization of neutron capture γ-rays.

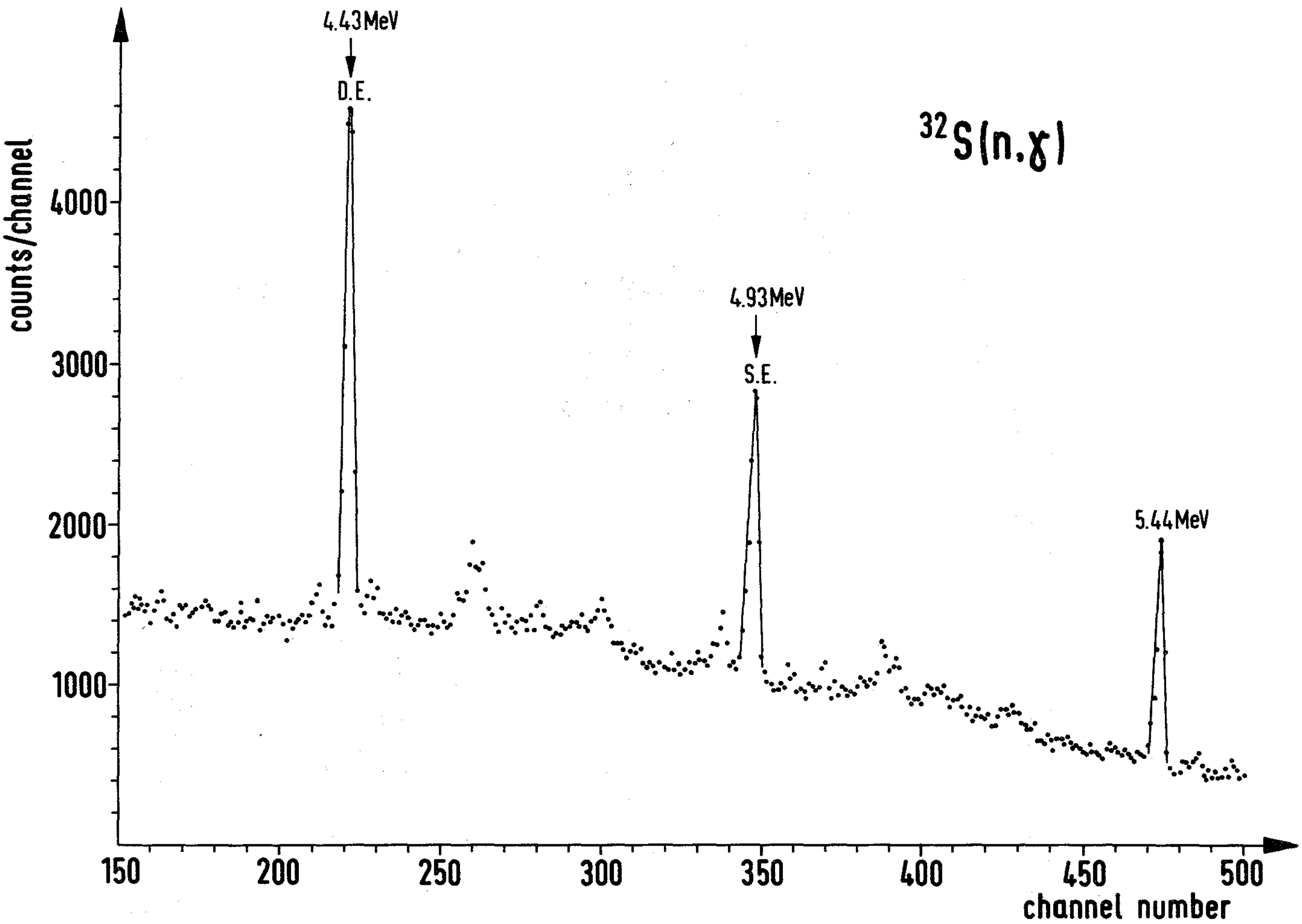

Fig. 2: Neutron capture γ-spectrum of ^{32}S, measured with a Ge(Li) detector.

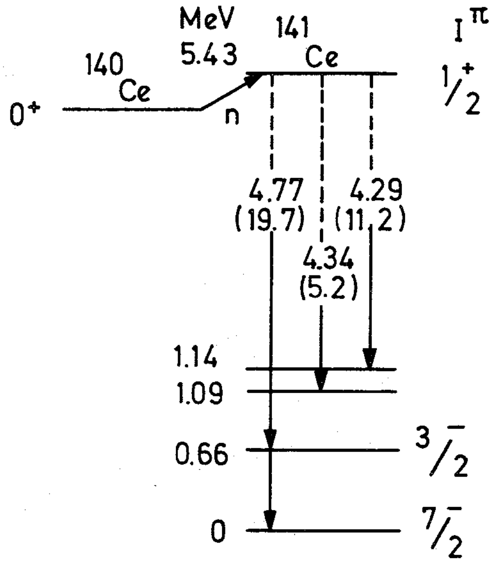

Fig. 3: Decay scheme for ^{141}Ce. The relativ intensities are given in brackets.

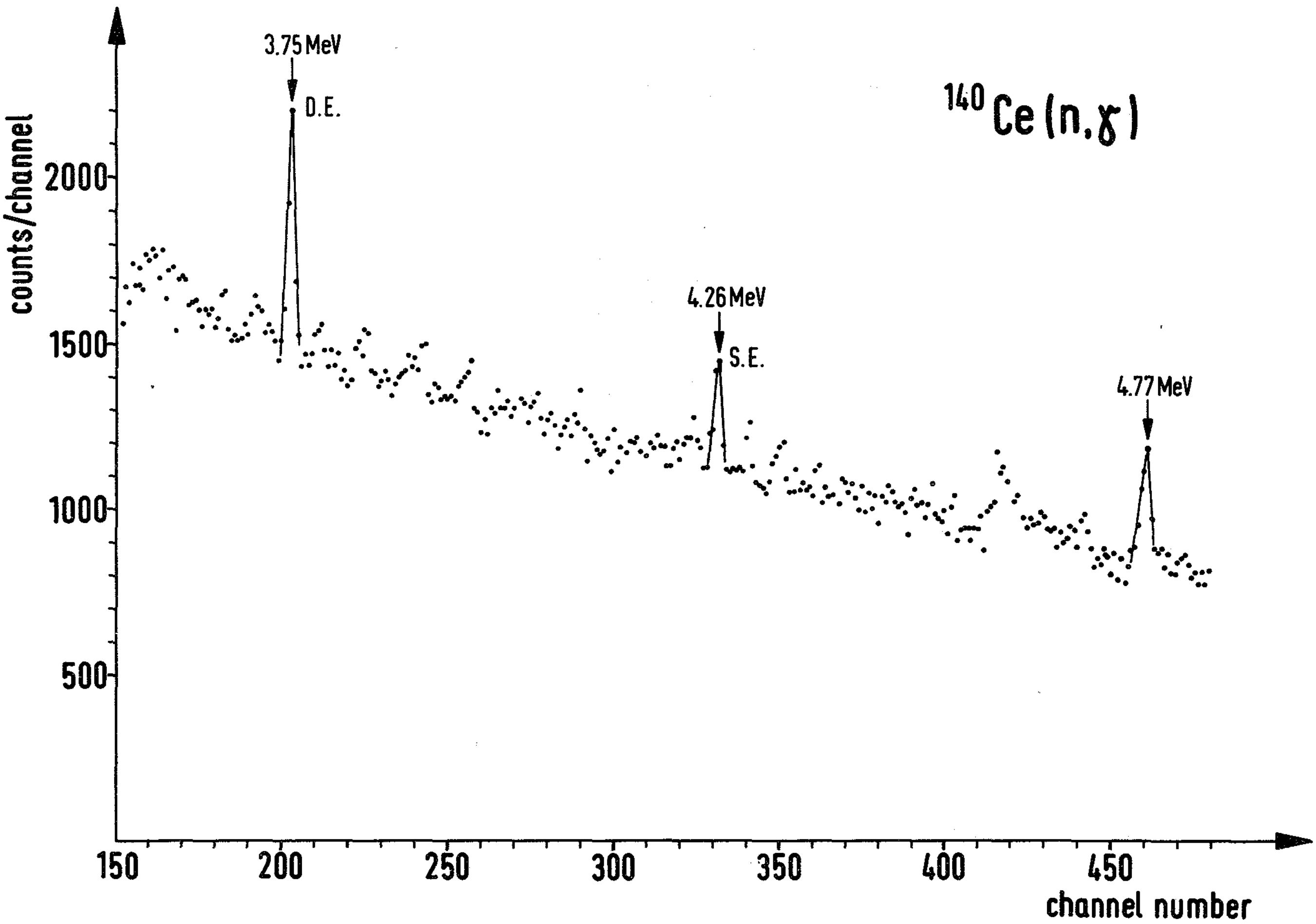

Fig. 4: Neutron capture γ-spectrum of ^{140}Ce, measured with a Ge(Li)-detector,target Ce_2O_3.

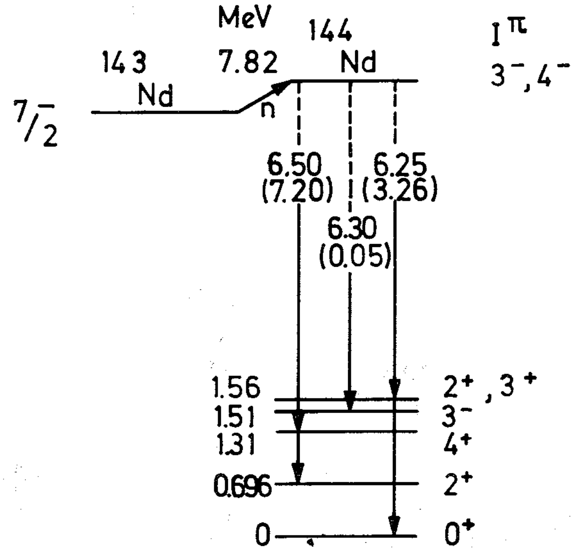

Fig. 5: Decay scheme for ^{144}Nd. The relativ intensities are given in brackets.

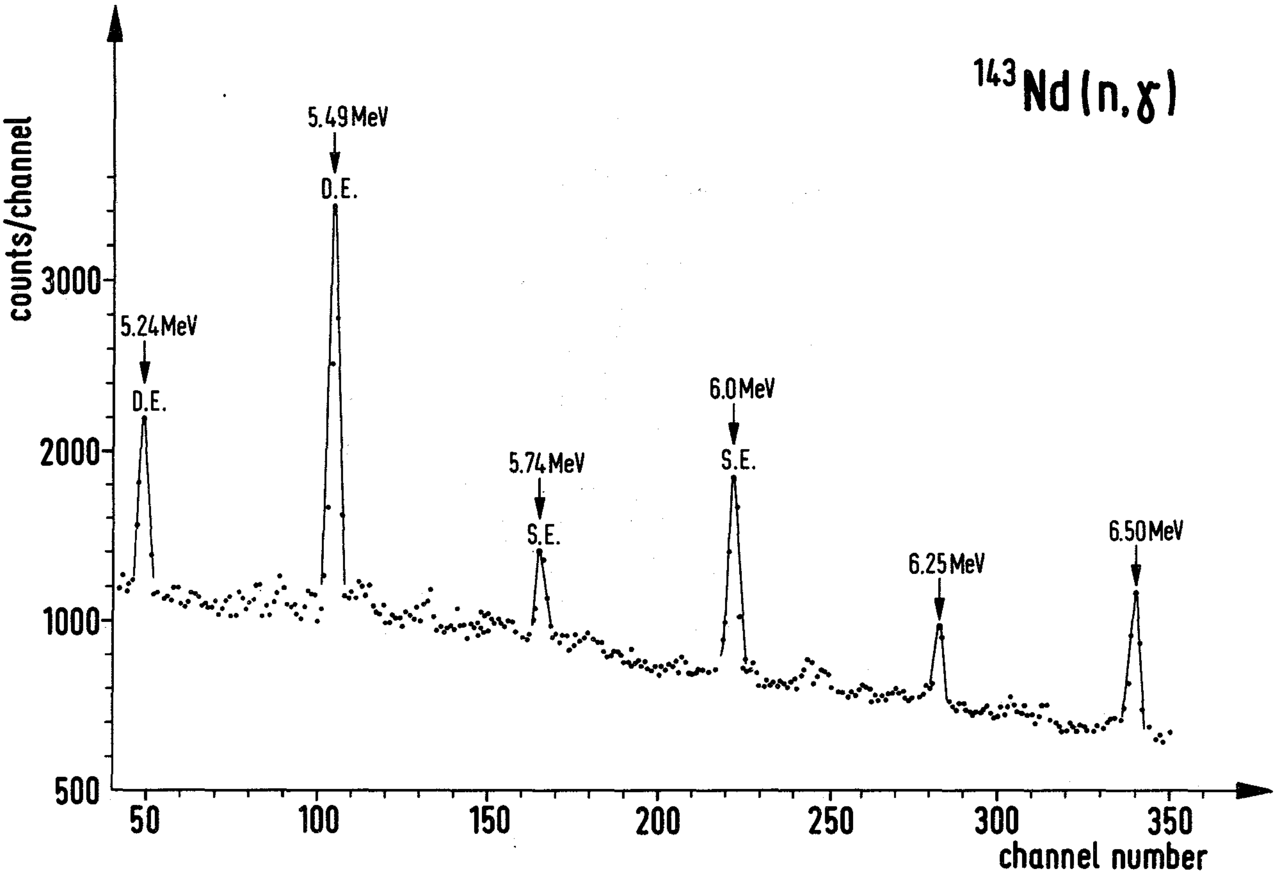

Fig. 6: Neutron capture γ-spectrum of ^{143}Nd, measured with a Ge(Li)-detector, target Nd_2O_3.

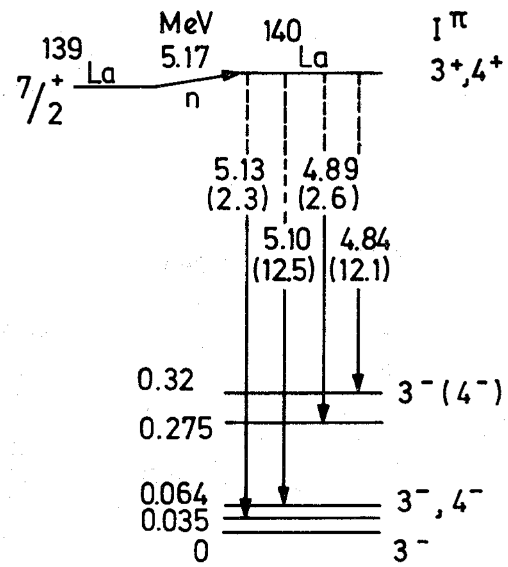

Fig. 7: Decay scheme for ^{140}La. The relativ intensities are given in brackets.

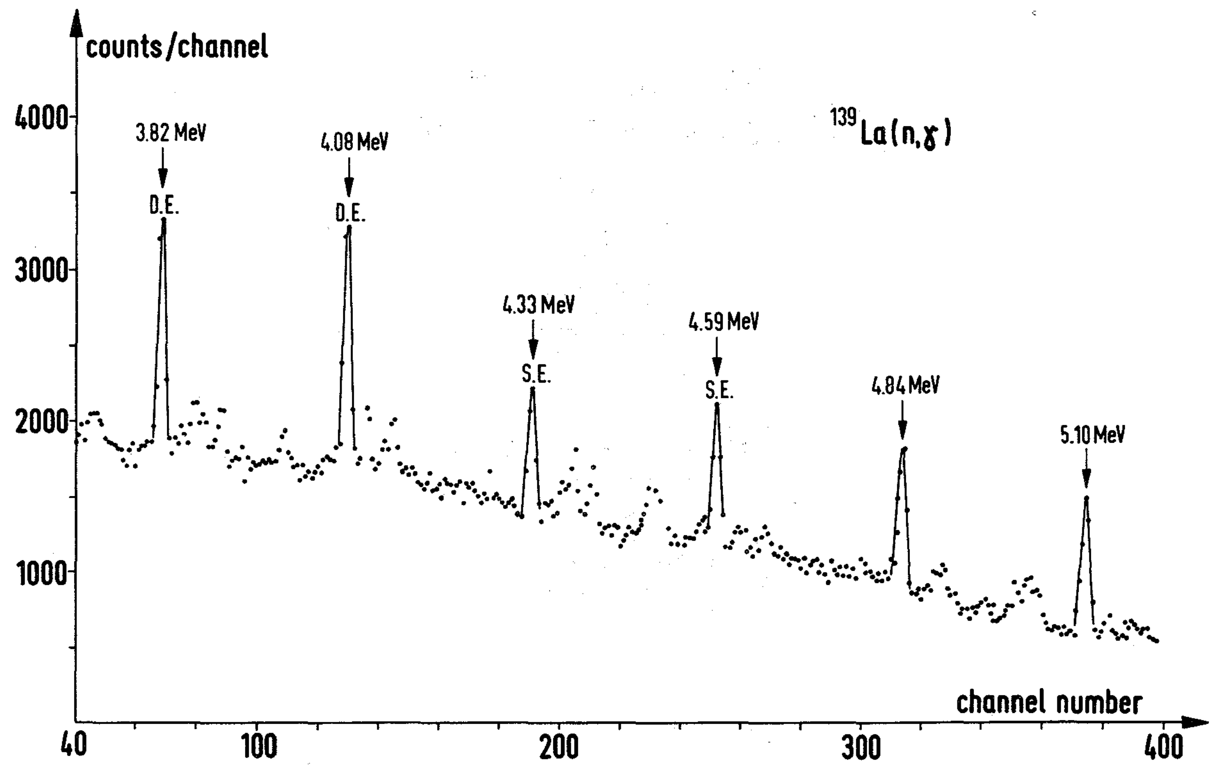

Fig. 8: Neutron capture γ-spectrum of ^{139}La, measured with a Ge(Li)-detector, target La_2O_3.

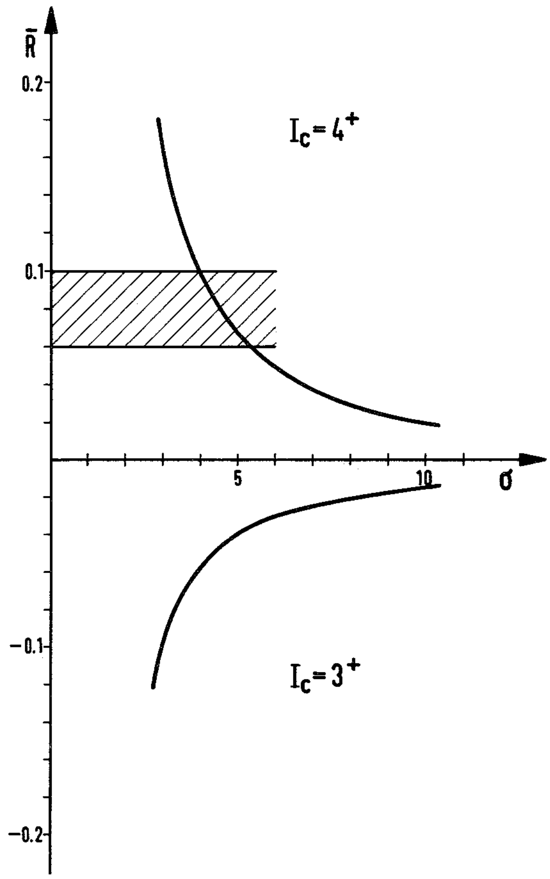

Fig. 9: Dependence of the average circular polarization R on σ for different compound-state spins I_c. The measured value for ^{140}La is included.