Time differential observation of the perturbed linear polarization distribution of γ radiation

W. Kreische, H. Niedrig, K. Reuter, K. Roth, and K. Thomas
Physikalisches Institut der Universität Erlangen-Nürnberg, Erwin-Rommel-Strasse 1, 8520 Erlangen, Germany
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The precession of the plane of polarization of γ radiation in an external magnetic field was observed time differentially. As this experiment is in full analogy to that done by Hanle in 1925 on atoms, we called this behavior nuclear Hanle effect. The measurement was performed with a pulsed proton beam of 5.5 MeV, which defined the moment of excitation of the 197 keV level in the ^{19}F nucleus. The result is well described by a simple theory in accordance with the theory of perturbed angular distributions.

[NUCLEAR REACTIONS $^{19}F(p,p')$, $E=5.5$ MeV; measured nuclear Hanle effect of ^{19}F (197 keV level), deduced g.]

INTRODUCTION

In the formulation of the theory of perturbed angular correlations (PAC's) with time independent interactions given by Leisi,[1] the PAC is interpreted as a quantum mechanical interference phenomenon.

One of the oldest experiments which demonstrates the importance of atomic coherence was done by Hanle in 1925,[2] who investiged the polarization of the scattered radiation in resonance fluorescence. The excitation of the atoms in a mercury vapor cell was effected by linear polarized light of a mercury lamp in order to get an alignment of the atomic states which is realized if the population parameters of the magnetic substates $|b_i\rangle$ fulfill the following condition:

$$P(b_i)=P(-b_i),\ \text{but}\ P(b_i)\neq P(b_j)\ \text{for}\ i\neq j\ .$$

Hanle found that the degree of polarization of the resonance light scattered by the atoms in the vapor cell could be diminished by a magnetic field applied parallel to the direction of observation of the emitted light. More detailed reviews of the Hanle effect are given by Kastler[3] and by Carrington.[4]

It was shown in recent papers[5,6] that the equivalent experiments could be done with nuclei where the alignment and the excitation were done by a nuclear reaction. In these experiments the dependence of the linear polarization of γ radiation from the strength of an external magnetic field was investigated with an experimental setup, where the axis of the magnetic field was parallel to the direction of observation and perpendicular to the beam axis. For a qualitative discussion of the time integral nuclear Hanle effect (NHE) it is useful to consider two extreme cases:

(1) $\hbar\omega_L \gg \Gamma$. The hyperfine splitting $\hbar\omega_L$ is larger than the natural line width Γ of the excited nuclear level; then the $\Delta M=\pm1$ components of the transition are right-hand circularly (RHC) and left-hand circularly (LHC) polarized. There is no interference and therefore also no linear polarization.

(2) $\hbar\omega_L \ll \Gamma$. The RHC and LHC polarized components cannot be distinguished energetically. Therefore they interfere, which leads to a linear polarization of the radiation.

With increasing magnetic field, which means increasing Zeeman splitting, the linear polarization decreases.

In this paper we discuss a NHE experiment with a pulsed accelerator beam. In this case it is possible to define the moment of excitation of the nuclei and therefore their decay can be observed differentially.

THEORY

We consider a pure transition from an excited nuclear level $|\mathcal{I}_b, b\rangle$ to a level $|\mathcal{I}_c, c\rangle$, where the ensemble of the excited nuclei is described relative to a z axis (in our case this will be the axis of the accelerator beam) by the population parameters $P(b)$ of the magnetic sublevels $|b\rangle$. If such a state $|b\rangle$ interacts with an external magnetic field or an axial symmetric electric field gradient, it is useful to choose the axis of quantization (z' axis) parallel to the field direction, as in the z' system the interaction Hamiltonian is diagonal. Generally the ensemble of excited nuclei must be transformed from the z to the z' system and the radiation field from the z' to z'' system, if the direction of observation (z'' axis) does not coincide with the z' axis. The transformations are performed by the three-dimensional rotation matrices $\alpha^{\mathcal{J}_b}_{bb'}(S)$ and $\mathfrak{D}^L_{Mq}(R)$, where S and R stand for the triple of the corresponding Euler angles. The transition amplitude for γ quanta with the circular polarization q is given by[7]

$$A^q(b,c) = -\left(\frac{k}{h}\right)^{1/2} \sum_{b'M} q^{\tau} e^{i(E_{b'}-E_c+i\Gamma/2)t/\hbar} (-1)^{\mathcal{J}_c-c} \begin{pmatrix} \mathcal{J}_c & L & \mathcal{J}_b \\ -c & M & b' \end{pmatrix} \langle \mathcal{J}_c \| T_L \| \mathcal{J}_b \rangle \mathfrak{D}^L_{Mq}(R) \alpha^{\mathcal{J}_b}_{bb'}(S) \quad . \tag{1}$$

In this formula it is assumed that the line width Γ is equal for all substates $|b\rangle$ and zero for the substates $|c\rangle$ (that means $|\mathcal{J}_c, c\rangle$ is assumed to be the ground state of the nucleus). The observed intensities of the radiation polarized parallel ($I_\parallel$) and perpendicular ($I_\perp$) to the zz'' plane respectively are the absolute values of the amplitudes weighted with the population parameters $P(b)$ and averaged over all substates $|c\rangle$,

$$I_{\parallel,\perp} = \sum_b P(b) \sum_c |A_{\parallel,\perp}(b,c)|^2 \tag{2}$$

with

$$A_{\parallel,\perp}(b,c) = \frac{1}{\sqrt{2}} (A^{-1}(b,c) \mp A^{+1}(b,c)) \; .$$

With the usual definition of the linear polarization one gets

$$p = \frac{I_\perp - I_\parallel}{I_\perp + I_\parallel} = \frac{\sum_b P(b)\left[\sum_{b_i'} \mathfrak{F}_{b_i'b_i'} + \sum_{(b_i'b_j')} |\mathfrak{F}_{b_i'b_j'}| \cos\left(\psi_{b_i'b_j'} + \frac{E_{b_i'} - E_{b_j'}}{\hbar} t\right)\right]}{\sum_b P(b)\left[\sum_{b_i'} F_{b_i'b_j'} + \sum_{(b_i'b_j')} |F_{b_i'b_j'}| \cos\left(\varphi_{b_i'b_j'} + \frac{E_{b_i'} - E_{b_j'}}{\hbar} t\right)\right]} \, , \tag{3}$$

where the following functions were introduced for abbreviation:

$$\begin{aligned} \mathfrak{F}_{b_i'b_j'} &= \mathfrak{F}^*_{b_j'b_i'} = \sum_{q_i q_j} F^{q_i q_j}_{b_i' b_j'} = |\mathfrak{F}_{b_i'b_j'}| \exp(i\psi_{b_i'b_j'}) \, , \\ F_{b_i b_j} &= F^*_{b_j b_i} = \sum_{q_i} F^{q_i q_i}_{b_i' b_j'} = |F_{b_i'b_j'}| \exp(i\varphi_{b_i'b_j'}) \, , \end{aligned} \tag{4}$$

with

$$F^{q_i q_j}_{b_i' b_j'} = F_0 e^{-\Gamma t/\hbar} q_i^{\tau} q_j^{\tau} \sum_{\substack{M_i M_j \\ j m m' \\ l n n'}} (-1)^{M_j - q_j + b - b_j' + n - n' + m - m'} (2j+1)(2l+1)$$

$$\times \begin{pmatrix} \mathcal{J}_c & L & \mathcal{J}_b \\ -c & M_i & b_i' \end{pmatrix} \begin{pmatrix} \mathcal{J}_c & L & \mathcal{J}_b \\ -c & M_i & b_j' \end{pmatrix} \begin{pmatrix} L & L & j \\ M_i & -M_j & m \end{pmatrix} \begin{pmatrix} L & L & j \\ q_i & -q_j & m' \end{pmatrix} \begin{pmatrix} \mathcal{J}_b & \mathcal{J}_b & l \\ b & -b & n \end{pmatrix} \begin{pmatrix} \mathcal{J}_b & \mathcal{J}_b & l \\ b_i' & -b_j' & n' \end{pmatrix}$$

$$\times \mathfrak{D}^j_{-m-m'}(R) \alpha^l_{-n-n'}(S) . \tag{5}$$

The function

$$F^{q_i q_j}_{b_i' b_j'}$$

contains all information about the nuclear spins and the geometry of the problem, where the hyperfine interaction appears only in the interference terms.

If the direction of observation of the γ quanta coincides with the z' axis in Eq. (1), all components of the rotation matrix $D^L_{Mq}(R)$ with $q \neq \pm 1$ vanish. For this special geometry of the NHE the interference terms in the denominator and the hard-core term in the numerator of Eq. (3) vanish. Then the polarization can be written in the following form:

$$p = \sum_{\substack{b_i' b_j' \\ b_i' \neq b_j'}} P_{b_i'b_j'} \cos\left(\psi_{b_i'b_j'} + \frac{E_{b_i'} - E_{b_j'}}{\hbar} t\right). \tag{6}$$

The factor $P_{b_i'b_j'}$ is different from zero only if

$$b_i' - c = -(b_j' - c) = \pm 1 \, . \tag{7}$$

Considering a γ transition with $\mathcal{J}_b = \frac{5}{2}$ and $\mathcal{J}_c = \frac{1}{2}$ and a pure time independent magnetic interaction with the magnetic field perpendicular to the direction of observation one gets

$$p = p_0 \cos(\psi + 2\omega_L t) \, , \tag{8}$$

where p_0 can be expressed in terms of the population parameters $P(b_i)$ by the equation[5]

$$p_0 = \frac{0.4P(\frac{1}{2}) + 0.6P(\frac{3}{2}) - 1.0P(\frac{5}{2})}{0.4P(\frac{1}{2}) + 1.0P(\frac{3}{2}) + 1.0P(\frac{5}{2})} \tag{9}$$

and ω_L is the Larmor frequency:

$$\omega_L = g\mu_N B/\hbar . \tag{10}$$

In this equation g is the g factor of the state $|\mathcal{J}_b\rangle$, μ_N is the nuclear magneton, and B is the external magnetic field.

EXPERIMENT

The measurement of the time differential nuclear Hanle effect was performed with the 197 keV γ radiation from the second excited state in ^{19}F ($J^\pi = \frac{5}{2}^+$, $\tau = 128.8$ nsec, $g = 1.476 \pm 0.016$).[8] This level was populated by the reaction ^{19}F$(p,p')^{19}F^*$ with a proton energy $E_p = 5.5$ MeV. The protons were stopped in the target, which was made of powder cubic crystalline CaF_2, pressed in form of a small disk. With this condition one gets a sufficient alignment of the ^{19}F-$\frac{5}{2}^+$ state, which was determined from the measured angular distribution shown in Fig. 1.

With the population parameters of the $\frac{5}{2}^+$ level obtained from a Legendre fit, the linear polarization could be determined according to Eq. (9). In addition one has to ensure that the population parameters are not changed during the lifetime of the excited state due to nuclear relaxation. This is true if $T_{rel} \gg \tau$. As the $\frac{5}{2}^+$ level in ^{19}F possesses a quadrupole moment $|Q| = (0.10 \pm 0.02) \times 10^{-24}$ cm^2 (Ref. 9) the angular distribution as well as the polarization can be perturbed by quadrupole interaction. To avoid such perturbations it is necessary to have the ^{19}F nuclei in a cubic lattice or in a liquid. If microcrystalline CaF_2 is used for the target it was shown by Heubes *et al.*[10] that the relaxation time is sufficiently long. The linear polarization of the radiation was measured with a usual Compton polarimeter described in Ref. 11. The sensitivity of the polarimeter was determined to be $r = 10$ for the 197 keV γ radiation, which means that for a 100% linear polarized radiation about 90% of the quanta are scattered perpendicular to the plane of polarization. In this energy range the Compton effect is therefore very sensitive to linear polarization.

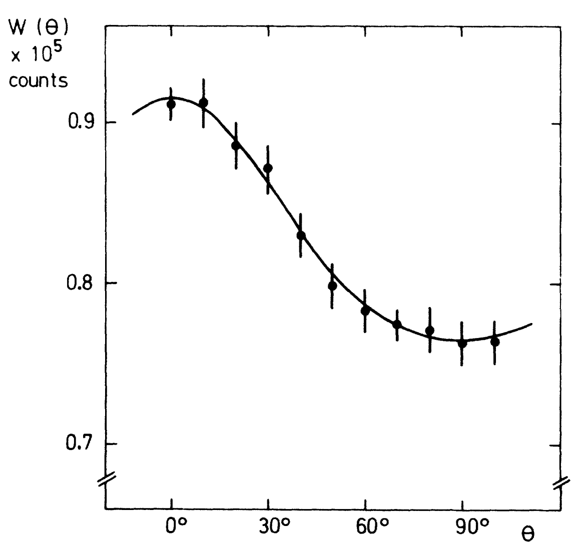

FIG. 1. Angular distribution of the 197 keV γ radiation in ^{19}F after a (p,p') reaction with $E_p = 5.5$ MeV (thick target).

The experimental setup was the same as described in Ref. 5. The external magnetic field was produced by an electromagnet with an axial hole in one pole cap which performed simultaneously the entrance diaphragm for the polarimeter. A schematic drawing of the setup is given in Fig. 2.

In order to do a time differential measurement of the NHE it is necessary to fix the moment of exciting the nuclear level. This was done by the use of a pulsed accelerator beam. The pulse frequency was 2 MHz corresponding to a pulse distance of about 500 nsec. The lifetime of the excited level was 128.8 nsec; therefore it was ensured that nearly all the activity was faded away until the occurrence of the next pulse. With a pulse width of full width at half maximum (FWHM) ≈ 10 nsec we obtained an averaged target current of about 5 nA. Because of the time resolution of the experiment, the Larmor frequency must be essentially smaller than 628 MHz; on the other hand, it should be as high as possible to get many ripples during the lifetime.

The magnetic field was therefore chosen to be $B = 8.7$ kG corresponding to a Larmor frequency of about 61 MHz. The electronics we used were standard; a schematic diagram of the circuit

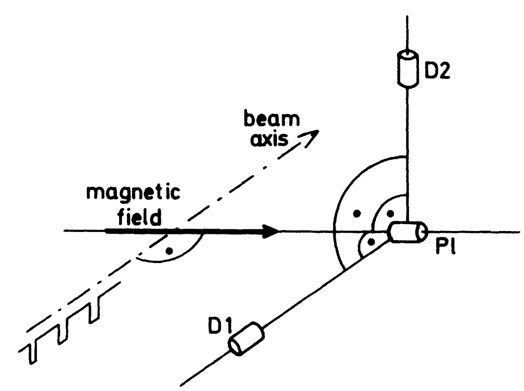

FIG. 2. Schematic drawing of the experimental setup.

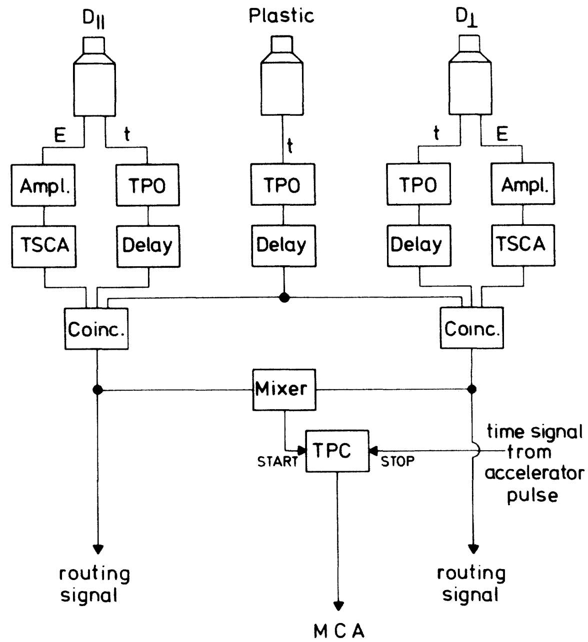

FIG. 3. Schematic circuit of the used electronics.

is shown in Fig. 3.

The TPC is started with the coincidence signal from the Compton polarimeter and stopped with the time signal of the accelerator pulse. Therefore in our TPC spectra the time axis goes from right to

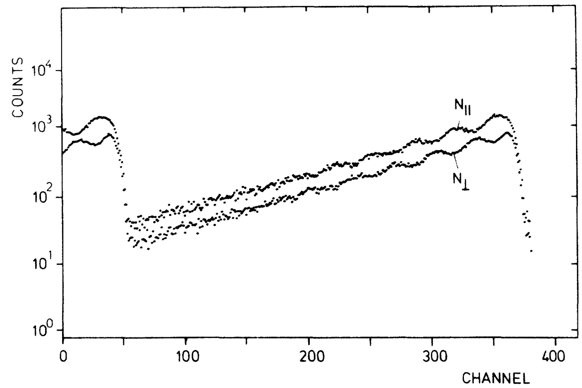

FIG. 4. TPC spectra of the two NaJ(Tl) detectors $D_\perp$ and $D_\parallel$ in the Compton polarimeter. (The scale at the left side is only valid for the rate $N_\parallel$.)

left. The obtained TPC spectra $N_\perp(t)$ and $N_\parallel(t)$ are shown in Fig. 4.

From the two spectra $N_\perp(t)$ and $N_\parallel(t)$ the expression

$$R(t) = \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel} \qquad (11)$$

was calculated channel by channel and fitted with the function

$$R(t) = R_0 \cos(2\omega t + \varphi) , \qquad (12)$$

where φ concerns beam bending, apparative asym-

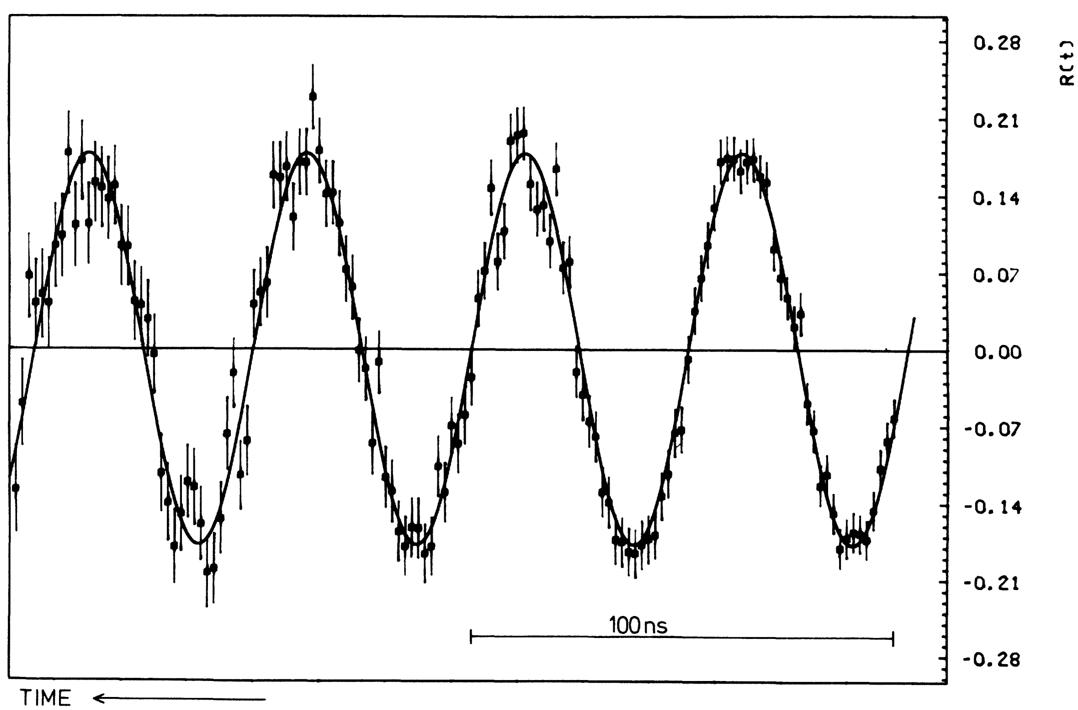

FIG. 5. Time dependence of the ratio R, which is proportional to the linear polarization, including a fit according to Eq. (12).

metry and the phase ψ in Eq. (8), The data including the fit are shown in Fig. 5.

The resultant frequency obtained from the fit is

$$\omega = 61.37 \pm 0.15 \times 10^6 \text{ sec}^{-1} . \qquad (13)$$

This leads, together with the magnetic field of

$$B = 8.7 \pm 0.2 \text{ kG}, \qquad (14)$$

to a g factor of the $\frac{5}{2}^+$ level of

$$g_{exp} = 1.47 \pm 0.03 . \qquad (15)$$

The experimental value is in good agreement with

$$g = 1.476 \pm 0.016 \qquad (16)$$

given by Ref. 8.

We also tried to fit the experimental values with a damped cosine function due to relaxation processes, but no damping could be observed. The maximum polarization was obtained from the fit (12) together with the sensitivity r of the polarimeter to

$$p_0 = \frac{r+1}{r-1} R_0 = 0.216 . \qquad (17)$$

DISCUSSION

As was shown in a recent paper,[6] the time averaged values of the linear polarization in a NHE experiment decrease with an increasing magnetic field, which can be described by two factors:

(1) a depolarization given by a factor of $[1 + (2\omega_L \tau)^2]^{-1/2}$ and

(2) a precession of the plane of polarization around the direction of the applied magnetic field given by the time averaged angle $\varphi_{rot} = 0.5 \arctan(2\omega_L \tau)$.

In a recent paper we discussed these two phenomena.[6] In a time differential observation no damping of the polarization occurs, therefore the precession of the plane of polarization can be seen directly. Equation (8) may be interpreted in this picture as the precession of the plane of polarization around the direction of the magnetic field with the frequency $2\omega_L$.

The absolute value of the maximum polarization can be increased by using an aqueous solution of BeF_2 as a target instead of solid CaF_2. This effect shows that there exists a short time relaxation process in a cubic lattice. Perhaps this depolarization process which takes part in less than some nanoseconds is caused by radiation damage of the CaF_2 lattice. There is some evidence that even in the cubic CaF_2 an electric field gradient is seen by a certain part of the excited nuclei after the nuclear reaction. Investigations of this electric field gradient and its temperature dependence are in progress.

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