Stroboscopic Observation of Nuclear Larmor Precession

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A new resonance method is described which is suited for the measurement of hyperfine interactions at nuclear isomers with mean lives longer than 1 μsec. The method is characterized by pulsed-beam production of excited nuclei, the Larmor frequency of which is determined by a coherent superposition of the perturbed angular correlation originating from different beam pulses. An experiment was performed on a 4-μsec state of ^{69}Ge. The g factor was determined as $g=-0.2224\pm0.0007$.

I. INTRODUCTION

RECENTLY, measurements of the magnetic hyperfine interaction of excited nuclei have frequently been performed using perturbed angular-correlation techniques following nuclear reactions. By this method the interaction between the nuclear magnetic moments and extranuclear magnetic fields can be studied. The observation of the perturbed angular-correlation pattern directly gives information about this interaction through determination of the Larmor frequency

$$\omega_L = g(\mu_N/\hbar)B_{\text{eff}}, \tag{1}$$

where g is the nuclear g factor and B_{eff} the time average of the total magnetic field at the nuclear position averaged over a time comparable to the Larmor period. In this paper, we will restrict our consideration to the case where the main part of B_{eff} is produced by an external magnetic field, and where the interaction of higher nuclear moments with the surrounding of the nucleus are neglected. Then a coherent precession of all nuclei under investigation is realized.

In pulsed-beam spin-precession experiments,[1,2] the Larmor precession of nuclei excited and aligned by a nuclear reaction can be determined by the time-differential measurement of the decay γ-ray angular distribution, i.e., one has to carry out a delayed-coincidence experiment between the exciting pulse and the subsequent γ-ray decay. Therefore, this method can only be applied as long as the meanlife τ of the excited state is shorter than the pulse-repetition time T_0. The coincidence condition limits the applicability of the method to lifetimes of about 1 μsec. Up to now, perturbed γ-γ angular correlation as well as pulsed-beam spin-precession experiments have only been performed at nuclear levels with lifetimes shorter than 0.5 μsec.[3]

The extension of the spin-precession method to excited states with considerably longer lifetimes can be achieved by the stroboscopic observation of the spin-precession. By these means, the unambiguous correlation between exciting pulse and subsequent γ decay is no longer necessary, so that many beam pulses may occur within the lifetime of the excited state ($\tau > T_0$). The new method depends on the observation of a resonance behavior of the perturbed γ-ray angular distribution. The resonance occurs if the Larmor frequency of the excited nuclei is equal to a multiple of half the pulse frequency. In this case, all excited nuclei precess with a constant phase with respect to the beam pulses, and one gets a coherent superposition of the intensity modulation produced by the perturbed angular correlation. A short review of this method has been given elsewhere.[4]

In the following, this new method will be discussed in more detail. In Sec. II, the basic formula of the resonance method will be deduced from the well-known theory of angular-correlation work. Section III deals with corrections to be applied as a consequence of experimental conditions. The influence of relaxation phenomena are described in Sec. IV. Results of the first experiment on a 4.1-μsec level of ^{69}Ge with $J^\pi = \frac{9}{2}^+$ are given in Sec. V. The nuclear properties of the lowest excited states of ^{69}Ge will be discussed in another paper.[5]

II. RESONANCE METHOD

The measurements to be described here are based on the following experimental arrangement: A pulsed particle beam is used to produce excited nuclei with a mean life considerably longer than the beam-pulse duration. An external magnetic field B at the target position is directed perpendicular to the beam axis. In the plane perpendicular to the field two NaI(Tl) γ detectors are mounted at angular positions θ_1 and θ_2 with respect to the beam direction. Then the observed γ intensity of the decaying state at a time t with respect to the beam pulse ($t=0$) is given by

$$I(\theta_{1/2}, t, B) \sim e^{-t/\tau} W(\theta_{1/2}, t, B), \tag{2}$$

where

$$W(\theta, t, B) = W(\theta - \omega_L t) = 1 + \sum_{k \text{ even}} A_k(1) A_k(2) P_k[\cos(\theta - \omega_L t)] \tag{3}$$

[1] R. M. Freeman, Nucl. Phys. **26**, 446 (1961).
[2] J. Bleck, D. W. Haag, W. Leitz, and W. Ribbe, Phys. Letters **26B**, 134 (1968).
[3] H. K. Walter, A. Weitsch, and P. Kienle, Z. Physik **175**, 520 (1963).
[4] J. Christiansen, H.-E. Mahnke, E. Recknagel, D. Riegel, G. Weyer, and W. Witthuhn, Phys. Rev. Letters **21**, 554 (1968).
[5] J. Christiansen, H.-E. Mahnke, E. Recknagel, D. Riegel, G. Schatz, and W. Witthuhn, Nucl. Phys. (to be published).

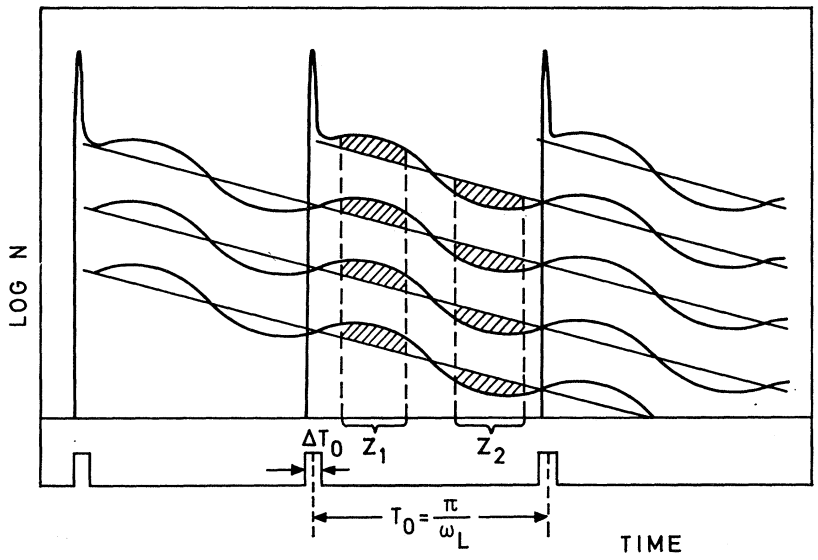

FIG. 1. Schematic illustration of the principle of the stroboscopic observation. In the resonance case $T_0=\pi/\omega_L$ shown here, the counting rates Z_1 and Z_2 are sensitive to the anisotropy of the perturbed angular correlation. The pulsed particle beam is characterized by the pulse-repetition time T_0 and the pulse width ΔT_0.

describes the perturbed angular correlation if internal perturbations are negligible.

The $A_k(1)$ depend on the nuclear reaction, whereas the $A_k(2)$ are determined only by the electromagnetic transition properties. Equation (3) can be written in the Fourier expansion:

$$W(\theta-\omega_L t)=\sum_{k\ \text{even}} b_k \cos k(\theta-\omega_L t). \qquad (3')$$

In the case $k_{\max}=2$, the coefficients b_0 and b_2 are given by

$$b_0=1, \qquad b_2=\tfrac{3}{4}A_2(1)A_2(2)/[1+\tfrac{1}{4}A_2(1)A_2(2)]. \qquad (3'')$$

The conditions $\Delta T_0 \ll \pi/\omega_L < \tau$ and $\tau < T_0$ are normally fulfilled in conventional spin-precession work. (ΔT_0 is the width of the beam pulse, T_0 is the length of the pulse interval.)

The *stroboscopic observation* can be achieved if $\tau > T_0$ and $\pi/\omega_L \leq T_0$. In this case, the correlation pattern is determined by two frequencies ω_L and $2\pi/T_0$, which leads to a resonance behavior of the time-dependent counting rates. One has to sum the γ-ray intensities originating from the decay of nuclei produced by different beam pulses (Fig. 1). The γ intensity during one pulse interval is given by

$$I(t,\tau,T_0,B,\theta) \sim \sum_{n=0}^{\infty} \exp[-(t+nT_0)/\tau]W[\theta-\omega_L(t+nT_0)]. \qquad (4)$$

Inserting Eq. (3), one gets

$$I(t,\tau,T_0,B,\theta)\sim e^{-t/\tau}\sum_{k\ \text{even}} b_k \frac{\cos k(\theta-\omega_L t)-\exp(-T_0/\tau)\cos k[\theta-\omega_L(t-T_0)]}{1-2\cos k\omega_L T_0\exp(-T_0/\tau)+\exp(-2T_0/\tau)} \qquad (4')$$

or

$$I(t,\tau,T_0,B,\theta)\sim e^{-t/\tau}\sum_k B_k\cos[k(\theta-\omega_L t)-\delta_k], \qquad (4'')$$

with

$$B_k=\frac{b_k}{[1-2\cos k\omega_L T_0\exp(-T_0/\tau)+\exp(-2T_0/\tau)]^{1/2}}, \qquad (5a)$$

$$\tan\delta_k=\exp(-T_0/\tau)\frac{\sin k\omega_L T_0}{1-\exp(-T_0/\tau)\cos k\omega_L T_0}. \qquad (5b)$$

As a consequence of these calculations, one gets a time-modulated decay spectrum containing frequencies $k\omega_L$ similar to the case of the conventional spin-precession method. But the modulation amplitudes are characterized by a typical resonance behavior depending on the relation between ω_L and $2\pi/T_0$.

The maxima of the modulation amplitudes occur with a Larmor frequency ω_{L0} at $k\omega_{L0}T_0=2n\pi$ ($n=\pm1, \pm2, \cdots$) with

$$(B_k)_{\max}=\frac{b_k}{1-\exp(-T_0/\tau)};$$

the minima occur at $k\omega_L T_0=(2n-1)\pi$ ($n=0, \pm1, \pm2, \cdots$) with amplitudes

$$(B_k)_{\min}=\frac{b_k}{1+\exp(-T_0/\tau)}.$$

In both cases the phase-shift constants δ_k vanish. The resonance behavior can be investigated by variation of one of the two characteristic frequencies. By changing B, i.e., the Larmor frequency, one gets a simple result: The amplitudes near the maxima have a resonance of the form

$$B_k=\frac{b_k}{T_0[(1/\tau)^2+k^2(\omega_L-\omega_{L0})^2]^{1/2}} \quad (6)$$

under the condition $\tau\gg T_0$.

The width of the resonance of the amplitude function B_2 is given by

$$\Delta\omega=1/\tau, \qquad \Delta\omega/\omega_{L0}=\Delta B/B_0=1/\omega_{L0}\tau=T_0/n\pi\tau, \quad (7)$$

using the definition of $\Delta\omega$ for amplitude functions:

$$B_2(\omega_{L0}\pm\tfrac{1}{2}\Delta\omega)=(1/\sqrt{2})B_2(\omega_{L0}).$$

The resonance occurs in a more conventional form if one looks at the intensity behavior at a fixed time t_0. Choosing the detector position θ and the fixed time t_0 in such a way that (for $k_{\max}=2$) in the resonance case the intensity is measured in the maxima or minima of modulation, one gets

$$I(t_0, \tau, T_0, B, \theta)\sim1\pm b_2\frac{(1/\tau)^2}{(1/\tau)^2+4(\omega_L-\omega_{L0})^2}. \quad (8)$$

{The maxima or minima of modulation means $\cos2(\theta-\omega_{L0}t_0)=\pm1$, or

$$t_0=[(2\theta-m\pi)/2n\pi]T_0=aT_0,$$
$$m=0, \pm1, \pm2\cdots, \qquad 0<a<1 \quad (9)$$

e.g., for $n=1$ and $\theta=\pm45°$ or $\pm135°$, the time is $t_0=\frac{1}{4}T_0$ or $\frac{3}{4}T_0$.}

The resonance curve is a Lorentzian with a *half-width* given by Eq. (7).

If the position θ and the time t_0 do not fulfill the condition (9), the more general form, including effects of angle deviation $\Delta\theta$ or time deviation $\Delta t_0=T_0\Delta\theta/n\pi$ is

$$I(t_0, \tau, T_0, B, \theta, \Delta\theta)\sim1\pm b_2 \times\frac{(1/\tau)^2\cos2\Delta\theta-2(1/\tau)(\omega_L-\omega_{L0})\sin2\Delta\theta}{(1/\tau)^2+4(\omega_L-\omega_{L0})^2}. \quad (10)$$

Especially for $\Delta\theta=\pi/4$, one gets

$$I\left(t_0, \tau, T_0, B, \theta, \frac{\pi}{4}\right)\sim1\pm b_2\frac{2(1/\tau)(\omega_L-\omega_{L0})}{(1/\tau)^2+4(\omega_L-\omega_{L0})^2}. \quad (11)$$

The resonance curve shows a dispersion behavior with maximum or minimum at $\omega_L=\omega_{L0}\pm1/2\tau$. The relation (10) is graphically shown in Fig. 2 for different $\Delta\theta$.

These line shapes are a consequence of the superposition of the amplitude resonance and the phase-shift

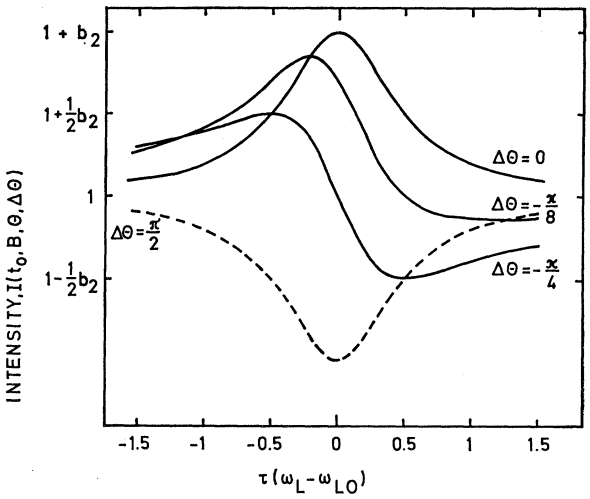

FIG. 2. Resonance behavior of the intensity $I(t_0, B, \theta, \Delta\theta)$ for different detector positions $\Delta\theta$, calculated from Eq. (10).

effects; the phase shift δ_2 shows a zero crossing at the resonance, whereas the shift is $\pm45°$ at the half-maximum points for the Lorentzian, and at the extreme values for the dispersion curve.

Using a finite time window $t_0-\Delta t\leq t\leq t_0+\Delta t$ with $\Delta t\leq\pi/\omega_L$, one gets in the first approximation ($1/\tau\ll 2\omega_L\approx2n\pi/T_0$) instead of (8):

$$I(t_0, \Delta t, \tau, T_0, B, \theta)\sim1\pm\frac{\sin2\omega_L\Delta t}{2\omega_L\Delta t}b_2 \times\frac{(1/\tau)^2}{(1/\tau)^2+4(\omega_L-\omega_{L0})^2}. \quad (12)$$

That means the finite width of the time window results in a small attenuation of the resonance effect.

A useful measure of the resonance effect is the intensity ratio of two special time windows

$$\frac{Z_1}{Z_2}=\frac{I(t_0, \Delta t, \tau, T_0, B, \theta)}{I(t_0\pm T_0/2n, \Delta t, \tau, T_0, B, \theta)}, \quad (13)$$

or the double ratio in a two-counter experiment:

$$\frac{Z_1}{Z_2}\frac{Y_2}{Y_1}=\frac{I(t_0, \Delta t, \tau, T_0, B, \theta)}{I(t_0\pm T_0/2n, \Delta t, \tau, T_0, B, \theta)} \times\frac{I(t_0\pm T_0/2n, \Delta t, \tau, T_0, B, \theta\pm90°)}{I(t_0, \Delta t, \tau, T_0, B, \theta\pm90°)}. \quad (14)$$

The $1/\tau$ dependence of the relative linewidth $\Delta\omega/\omega$ leads to the consequence that measurements of the hyperfine interaction can be performed with high precision. There are still many problems in making use of this precision in nuclear as well as in solid-state physics, e.g., the magnetic hyperfine anomaly (Bohr-Weisskopf effect), Knight-shift phenomena, paramagnetic fields, nuclear spin interactions in solids. etc. In nuclear reactions, implantation of the recoils under investigation in different lattices can be realized. This fact considerably differentiates the basis of such experiments.

Therefore, it seems to be worthwhile to give a more detailed description of the corrections which have to be taken into account to perform precision experiments using the stroboscopic method.

III. CORRECTIONS OF RESONANCE LINE

The discussion will be restricted to the method of variation of the external field under the condition of counting within a fixed time window and assuming a stable pulse frequency and a constant and homogeneous magnetic field. Corrections will be given only for the case $k_{\max}=2$.

The stroboscopic resonance curve is affected by the following specific parameters:

(a) correlation between the detector angle θ and the position of the time window t_0,
(b) width of the time window Δt,
(c) influence of the magnitude of the anisotropy coefficient b_2,
(d) width of the pulse interval ΔT_0, and
(e) influence of the ratio T_0/τ.

As will be shown in the following, the influence of (a) and (b) produces a shift of the resonance, while (b), (c), and (e) affect the width of the resonance. The finite pulse interval ΔT_0 [(d)] causes a fixed phase-shift relation between precessing nuclei which affects the resonance in a similar way as the finite time window Δt [(b)] does.

A. Shift of Resonance

As demonstrated in Fig. 2, the resonance curve is symmetric when the center of the time window and the detector angle fulfill Eq. (9). Otherwise the resonance curve becomes asymmetric and the maximum is shifted. For small deviations $\Delta\theta\ll\pi/4$, which means $\Delta t_0=T_0\Delta\theta/n\pi\ll\pi/4\omega_{L0}$, the shift is given by

$$(\omega_L-\omega_{L0})/\omega_{L0}=\tfrac{1}{2}(\Delta\theta/n\pi)(T_0/\tau)[1-(2-a)T_0/\tau]^{-1}$$
$$=\tfrac{1}{2}(\Delta t_0/\tau)[1-(2-a)T_0/\tau]^{-1}. \quad (15)$$

In the case of the ^{69}Ge level, for instance, one has $T_0/\tau\approx\frac{1}{4}$. A disalignment of $\Delta\theta=4°$ results in a shift of 3×10^{-3} for $n=1$ and 6×10^{-4} for $n=5$. These shifts are slightly reduced in a two-counter experiment. Equation (15) shows that, for a careful time-angle adjustment, shifts and asymmetries of this type can be neglected even in high-precision experiments.

Because of the exponential decay, the finite width $2\Delta t$ of the time window results in an attenuation and in a slight asymmetry of the resonance. In a one-counter–two-time window (or a two-counter–two-time window) experiment, the asymmetry effect nearly cancels out: For $T_0/\tau=\frac{1}{4}$, one gets an asymmetry effect of

$$A=\|(\omega_{L0}-\omega_-)/(\omega_{L0}-\omega_+)\|-1|<10^{-3}$$

for the intensity ratio Z_1/Z_2. (ω_- and ω_+ are the frequencies defining the half-width.)

B. Width of Resonance

Measuring the intensity ratios Z_1/Z_2 or $(Z_1/Z_2)\times(Y_2/Y_1)$, the magnitude of the anisotropy coefficient b_2 influences the half-width. In the Lorentzian approximation, the half-width is given by

$$\Delta\omega=(1/\tau)(1\mp b_2)^{1/2}\begin{cases}- & \text{for } Z_1/Z_2>1\\ + & \text{for } Z_1/Z_2<1\end{cases} \quad (16a)$$

for the ratio Z_1/Z_2, and

$$\Delta\omega=(1/\tau)(1\mp2b_2+\tfrac{3}{2}b_2^2\mp\tfrac{1}{2}b_2^3)^{1/2} \quad (16b)$$

for the double ratio $(Z_1/Z_2)(Y_2/Y_1)$.

The average value of the two possible double ratios agrees quite well with the natural linewidth

$$\langle\Delta\omega\rangle_{\rm av}=(1/\tau)(1+\tfrac{1}{4}b_2^2+\cdots), \quad (17)$$

e.g., for $b_2=0.1$ the deviation is only about 2.5%.

$$\Delta\omega=(1/\tau)\left[\frac{1\mp b_2-T_0/\tau\pm b_2T_0/\tau+(7/12)(T_0/\tau)^2}{1-T_0/\tau\pm b_2T_0/4\tau+\frac{13}{16}(T_0/\tau)^2}\right]^{1/2}. \quad (18)$$

The attenuation of the resonance effect by the finite time window introduces a correction dependent on the magnitude of Δt. As a consequence, the coefficient b_2 has to be replaced by $(\sin2\omega_L\Delta t/2\omega_L\Delta t)b_2$.

IV. INFLUENCE OF RELAXATION PHENOMENA

So far, the stroboscopic resonance has been discussed assuming that the nuclear alignment and the phase of the precessing nuclei are preserved during their lifetime. This assumption does not hold if relaxation phenomena occur in the target material and the relaxation time is comparable with the lifetime of the nuclear state.

For an exponential decay of the anisotropy[6] with the relaxation time $T_{\rm rel}$, the angular distribution can be written

$$W(\theta,t,B)=1+A_2(1)A_2(2)$$
$$\times\exp(-t/T_{\rm rel})P_2(\theta-\omega_Lt)+\cdots. \quad (19)$$

As a consequence, the resonance will be attenuated and broadened. In the case of $k_{\max}=2$, Eq. (8) has to be replaced by

$$I(t_0,\tau,T_{\rm rel},T_0,B,\theta)\sim1\pm\frac{\frac{3}{4}A_2(1)A_2(2)}{1+\tau/T_{\rm rel}+\frac{1}{4}A_2(1)A_2(2)}$$
$$\times\frac{(1/\tau+1/T_{\rm rel})^2}{(1/\tau+1/T_{\rm rel})^2+4(\omega_L-\omega_{L0})^2} \quad (20)$$

under the assumption τ, $T_{\rm rel}\gg T_0$. Instead of Eq. (7), the linewidth is now given by

$$\Delta\omega=1/\tau+1/T_{\rm rel},\qquad \Delta B/B_0=(1/\omega_{L0})(1/\tau+1/T_{\rm rel}). \quad (21)$$

[6] A. Abragam and R. V. Pound, Phys. Rev. **92**, 943 (1953).

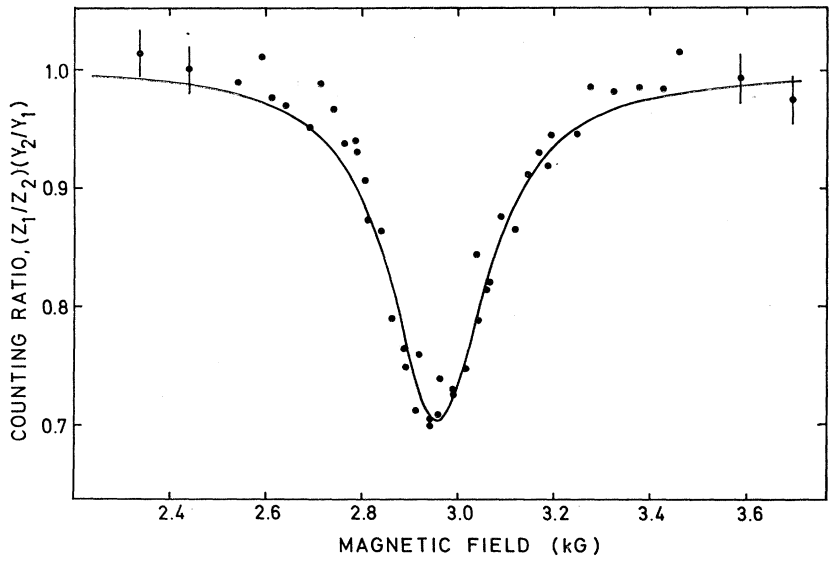

FIG. 3. Stroboscopic resonance of the perturbed angular correlation of the 398-keV γ rays following the reaction ^{69}Ga$(p,n)^{69}$Ge as a function of the applied field. The solid line is calculated from Eq. (14) with $\tau=4.1$ μsec.

Therefore, relaxation phenomena limit the investigations of long-lived states by the stroboscopic method.

V. EXPERIMENT AND RESULTS

The measurement of the strobscopic resonance on the $\tau=4.1$ μsec, 398-keV $(\frac{9}{2})^+$ level in ^{69}Ge was performed using the ^{69}Ga$(p,n)^{69}$Ge reaction to populate the excited state.[5] The liquid-gallium target was bombarded with protons of energy 4.4 MeV. Figure 3 shows the intensity distribution as a function of the external magnetic field.

The double ratio $(Z_1/Z_2)(Y_2/Y_1)$ of the two-counter–two-time window system was determined using the following parameters:

$$Z_1:\ t_0=\tfrac{1}{4}T_0,\ \Delta t,\ \theta_1=45°;$$
$$Z_2:\ t_0=\tfrac{3}{4}T_0,\ \Delta t,\ \theta_1=45°;$$
$$Y_1:\ t_0=\tfrac{1}{4}T_0,\ \Delta t,\ \theta_2=-45°;$$
$$Y_2:\ t_0=\tfrac{3}{4}T_0,\ \Delta t,\ \theta_2=-45°.$$

The width of the time window was $2\Delta t=200$ nsec. The pulse frequency $2\pi/T_0=1.0000\times10^6$ cycles/sec and the width of the beam pulses $\Delta T_0=10$ nsec were specified by the internal pulsing system of the van de Graaff accelerator. The solid line of Fig. 3 is calculated from Eq. (14) using the parameter $\tau=4.1$ μsec, $T_0=1$ μsec, $\Delta t=100$ nsec, $\theta_1=+45°$, $\theta_2=-46.8°$, $b_2=0.093$, and the magnetic resonance field

$$B_0=2.950\pm0.015\ \text{kG}. \tag{22}$$

The full width at half-maximum (FWHM) of the calculated curve was

$$(\Delta B_{1/2})_{\text{theor}}=249.0\ \text{G}.$$

From the experimental data, the FWHM of the ratio $(Z_1/Z_2)(Y_2/Y_1)$ was determined to be $(\Delta B_{1/2})_{\text{expt}}=250\pm15$ G. The corresponding values of the inverted ratio $(Z_2/Z_1)(Y_1/Y_2)$ are $(\Delta B_{1/2})_{\text{theor}}=209.8$ G and $(\Delta B_{1/2})_{\text{expt}}=210\pm15$ G. The mean value of the experimental data

$$\Delta B_{1/2}=230\pm10\ \text{G} \tag{23}$$

is to be compared with the natural linewidth deduced from the meanlife $\tau=4.1\pm0.1$ μsec:

$$(\Delta B_{1/2})_{\text{nat}}=230\pm5\ \text{G}. \tag{24}$$

These values indicate a lower limit of the relaxation time of oriented Ge atoms in liquid gallium of

$$T_{\text{rel}}>100\ \mu\text{sec} \tag{25}$$

at a target temperature of about 40°C.

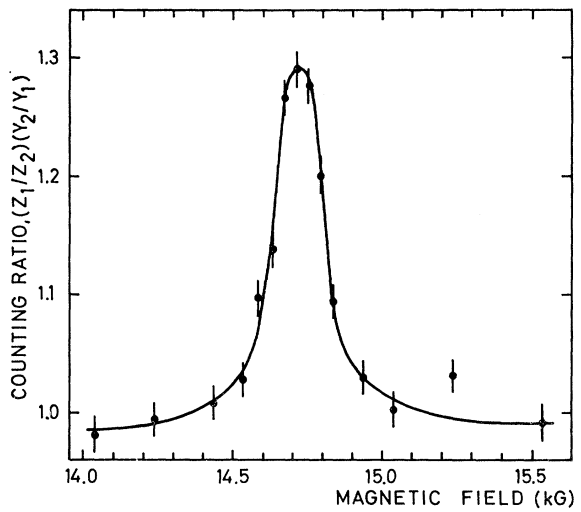

FIG. 4. Stroboscopic resonance at the fifth harmonics ($n=5$). The time windows are symmetric to the extreme values of the intensity modulation (see Fig. 1), with a width of $2\Delta t=70$ nsec.

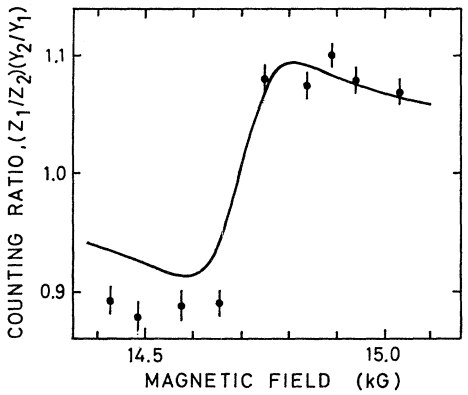

FIG. 5. Stroboscopic resonance at the fifth harmonics ($n=5$). The time windows are symmetric with respect to the zero crossings, with a width of $2\Delta t=50$ nsec. The solid line is calculated from Eq. (14) using Eq. (11). The deviations of the measured points are due to unequal background in the two-counter systems.

In a similar way as described above, the behavior of the resonance was studied at the fifth harmonics ($n=5$) of the Larmor frequency in the 1 Mc/sec pulsing system. In the case of the Lorentzian curve (Fig. 4), the time windows were placed at the maxima and minima of the modulation function, while in the case of the dispersion curve (Fig. 5), the time windows were shifted by 50 nsec corresponding to the zero crossings of the modulation. The resulting resonance field was

$$B_0=14.70\pm0.05\text{ kG} \qquad \text{at } n=5. \tag{26}$$

The solid line of Fig. 5 was calculated from Eqs. (11) and (14), using the corresponding parameters and $b_2=0.043$, $\Delta t=25$ nsec. The deviation of the curve from the experimental counting ratios is due to unequal background in the two counter systems, the influence of which was not taken into account.

The total magnetic field acting at the nuclear position can be written neglecting internal perturbation fields produced by all types of radiation damage:

$$B=B_{\text{ext}}(1+K)(1-\sigma), \tag{27}$$

where K is the Knight-shift constant and σ describes all effects of chemical shift. The Knight shift is known in liquid Ga, at a temperature slightly above the melting point at the nuclear position of Ga atoms, as $K=\Delta B/B=4.49\pm0.04\times10^{-3}$.[7] A measurement of the shift in the case of Ge atoms in Ga is being prepared. As a first approximation we used the value at the Ga nuclei for correction of our resonance field. The main part of the chemical shift is given by the diamagnetic shielding of the electronic shells. The shielding constant σ is[8] $\sigma=2.8\times10^{-3}$ for $Z=32$.

[7] H. S. Gutowsky and B. R. McGarvey, J. Chem. Phys. **20**, 1472 (1952).

[8] V. S. Shirley, in *Hyperfine Structure and Nuclear Radiations*, edited by E. Matthias and D. A. Shirley (North-Holland Publishing Co., Amsterdam, 1968), p. 985.

From the corrected resonance field of

$$(B_0)_{\text{corr}}=2.951\pm0.010\text{ kG},$$

the g factor of the 398-keV level is deduced to be

$$g_{\text{corr}}=-0.2224\pm0.0007.$$

The negative sign is a consequence of the positive slope of the dispersion curve of Fig. 4 (lower curve) after it was shown experimentally that the counting rate at $t=0$ has a maximum at $\theta=0°$.

VI. CONCLUSION

According to the features of the new method contained in this paper, the range of application can be summarized in the following points.

(a) To determine the hyperfine interaction of isomeric states, the method makes accessible a new range of lifetimes (10^{-6}–10^{-2} sec). There is no limitation on counting rates in the method, so that high statistical accuracies can be realized during reasonable measuring times.

(b) Because of the fact that the resonance curve shows the natural linewidth in the unperturbed case, the hyperfine interaction can be determined with high precision. Furthermore, the relative accuracy can be considerably increased by the measurement of the higher harmonics of the resonance. For the range of lifetimes mentioned in (a), the linewidths are 10^{+2}–10^{-2} G.

(c) As a result of these narrow lines, it is possible to determine very small additional interactions between the nuclear moments and the surrounding electric and magnetic fields from the broadening, the shift, and the splitting of the resonance curves. This could be especially important in solving solid-state problems.

(d) The recoil of the final nuclei, caused by the reaction mechanism, makes it possible to implant these nuclei into different materials. Thus each nucleus can be used as a probe to study the properties of the host lattice.

(e) The choice of the target material and its physical condition is not restricted by the method, but only by the existence of appropriate isomeric states. Investigations could be carried out with small amounts of enriched isotopes.

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