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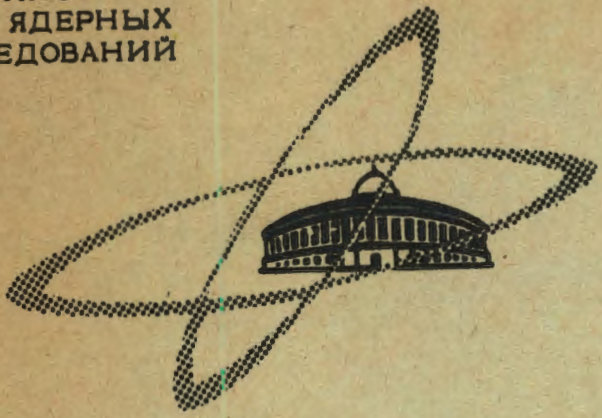

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A.Z.Hrynkiewicz

MAGNETIC MOMENT MEASUREMENTS FOR SHORT-LIVED NUCLEAR STATES

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MAGNETIC MOMENT MEASUREMENTS FOR SHORT-LIVED NUCLEAR STATES

(Lecture at the University of Helsinki)

1. Introduction

In this lecture I would like to give a general review of the methods used to measure the magnetic moments of short-lived nuclear states and to present in more detail the principles, possibilities and limitations of methods based on the Mössbauer effect and on the angular correlations of nuclear radiations. I would like also to discuss the application of internal magnetic fields and to describe some methodical refinements introduced recently.

Any experimental method of determining of nuclear magnetic moments is based on their interaction with the magnetic field. In the magnetic field of the intensity H the nucleus performs Larmor precession with the frequency

$$\vec{\omega} = -g \frac{\mu_N}{\hbar} \vec{H} ,$$

where μ_N is the nuclear magneton, the nuclear g-factor being the ratio of the nuclear magnetic moment to the nuclear spin. Using the numerical value $\mu_N = 3.15.10^{-12}$ eV/G, we obtain $\omega = -4,79.10^3 H$, where H is expressed in gauss.

The Larmor precession frequency vector $\vec{\omega}$, for positive g -factors, is antiparallel to the magnetic field intensity $\vec{H}$.

Nuclear level splitting corresponding to the precession frequency ω is equal to

$$\Delta E = \hbar\omega .$$

In order to determine the nuclear g -factor the Larmor precession frequency in a known magnetic field should be either directly measured or deduced from the level splitting ΔE . The sign of the g -factor can be established when it is possible to determine the direction of the nuclear precession with respect to the direction of the magnetic field.

My lecture concerns short-lived nuclear states, but let me first remind you of the methods of magnetic moment determination for ground states of stable nuclei and for states living longer than say 10 minutes. The majority of measurements in this life-time region (more than 70%) were performed using one of the following three methods:

1. Nuclear magnetic resonance (NMR)
2. Atomic beam resonance (ABR)
3. Atomic spectroscopy (AS).

The first two are very accurate, as the resonance frequency can be determined with high precision. The main source of error lies in the determination of the intensity of the applied magnetic field and in the calculation of diamagnetic corrections.

The atomic spectroscopy measurements are much less accurate. They require the knowledge of the atomic magnetic fields, which are difficult to calculate with good precision.

In the case of radioactive nuclei, the application of the listed methods is limited by the amount of available material and by the life-time of investigated nuclear states. These two factors are clo-

sely related. The shorter the life-time of a nuclear state, the smaller number of nuclei in this state can be used in the experiment.

The NMR measurements require a macroscopic amount of substance. Up to now, ^{3}H is the shortest-living nucleus ($T_{1/2}$ = = 12.3 years), for which the conventional NMR technique was successfully applied[1].

In optical spectroscopy far less material is needed. Its amount should be sufficient to provide enough light for hyperfine structure studies, keeping the exposure time reasonably short. In the favourable cases the atomic spectroscopy can be applied to nuclear states with life-times of a few hours.

In the atomic beam resonance, nuclear radiation of the investigated isotopes may be used for indication of resonance conditions. This leads to a much lower limit of the required number of nuclei and the magnetic moments of nuclear states living only a few minutes become accessible.

The region of life-times $10^{2}\,s > \tau > 10^{-6}\,s$ is very hard to approach. Measurements in this region may be performed using the combination of nuclear magnetic resonance and nuclear techniques. I shall give a few examples of such a sophistication at the end of my lecture.

2. Nuclear Techniques Used for Magnetic Moment Measurements

For life-times shorter than $10^{-6}\,s$ different nuclear methods can be applied, the most common of which are:

1. Mössbauer effect for magnetic substances (ME),
2. Perturbed angular correlations of nuclear radiations (PAC)

3. Perturbed angular distribution (PAD)

a) of gamma rays emitted by products of nuclear reactions (NR) or by Coulomb excited nuclei (CE)

or b) of resonant scattered gamma rays (RS).

In principle the third group of methods (PAD) is very similar to the method of perturbed angular correlations (PAC). The main difference is the way of producing unequal population of magnetic substates. In the PAC experiments it is accomplished through detection of the preceeding radiation in a defined direction. In the PAD methods it is the consequence of the defined direction of the bombarding ion beam (NR and CE) or of the direction of the primary gamma ray (RS). Because of this similarity of PAC and PAD methods I shall not discuss the latter and concentrate only on the application of the Mössbauer effect and the perturbed angular correlations.

2.1. Mössbauer Technique of Magnetic Moment Measurements

In Mössbauer experiments with magnetic substances we observe Zeeman splitting of gamma transitions due to interaction of nuclear magnetic moments with the internal magnetic field. The nuclear g-factor of the excited states as well as the internal field intensity can be measured in the same experiment, provided that we know the g-factor of the nuclear ground state.

Let us take the classical example of the 14.4 keV transition in ^{57}Fe embeded in an iron foil. In the internal magnetic field the ground state of ^{57}Fe, with $I = 1/2$, splits into two components and the 14.4 keV state, with $I = 3/2$, into four components.

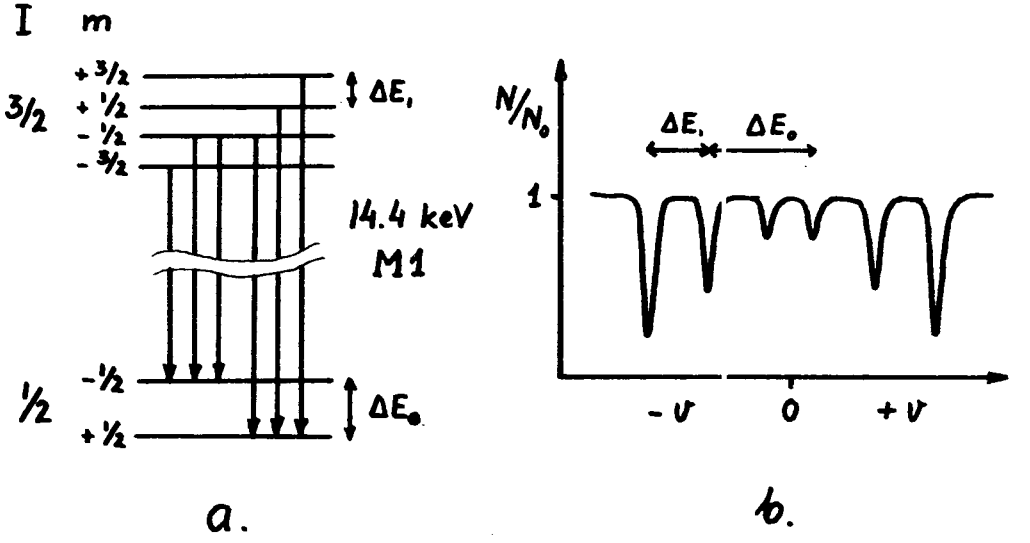

Fig.1. a) Zeeman splitting of the ground level and the 14.4 keV level of ^{57}Fe.
b) Sketch of the Mössbauer spectrum.

This is illustrated in Fig.1a. The splitting energies are equal to

$$\Delta E_0 = g_0 \mu_N H$$

and

$$\Delta E_1 = g_1 \mu_N H$$

for the ground and the excited states respectively.

Because of the M1 character of the 14.4 keV transition, the selection rule $\Delta m = 0, \pm 1$ should be obeyed and 6 hyperfine structu-

re components are seen in the Mössbauer pattern (Fig.1b). Measuring E_0 and E_1 and using the known value of $g_0 = +0.1805$ the internal magnetic field $H = 337$ kG and the g-factor of the 14.4 keV state $g_1 = -0.1031$ can be obtained.

The first g-factor measurement using the Mössbauer technique was performed for ^{57}Fe by Hanna et al.[2] in 1960.

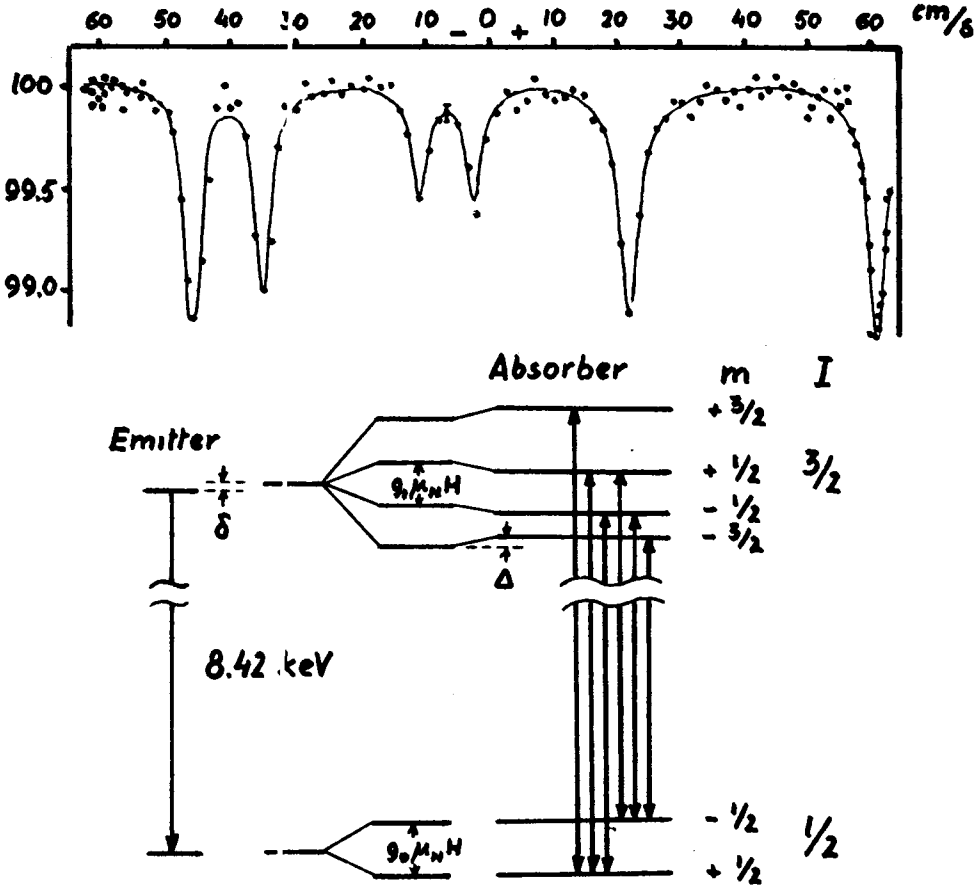

Fig.2. Mössbauer pattern of the 8.42 keV transition of ^{169}Tm in Tm-metal at 5°K and the hyperfine splitting of the 8.42 keV state and the ground state of ^{169}Tm[3]. δ-Isomer shift, Δ-electric quadrupole interaction.

Fig.2 taken from the work of Kalvius et al.[3] shows a more complicated case of the 8.42 keV transition in ^{169}Tm in Tm-metal, where in addition to the magnetic interaction the quadrupole interaction is present. This experiment was performed in liquid helium temperature. The magnetic field acting on Tm nuclei in Tm-metal $H = 6,96.10^6$ g and the g-factor for the 3.9 ns, 8.42 keV state $g = 0.356$ (10) were obtained.

In 1965 the Mössbauer effect was successfully applied by Seyboth et al.[4] and by Lee et al.[5] to the investigation of Coulomb excited gamma transitions, which considerably extended the possibilities of this method.

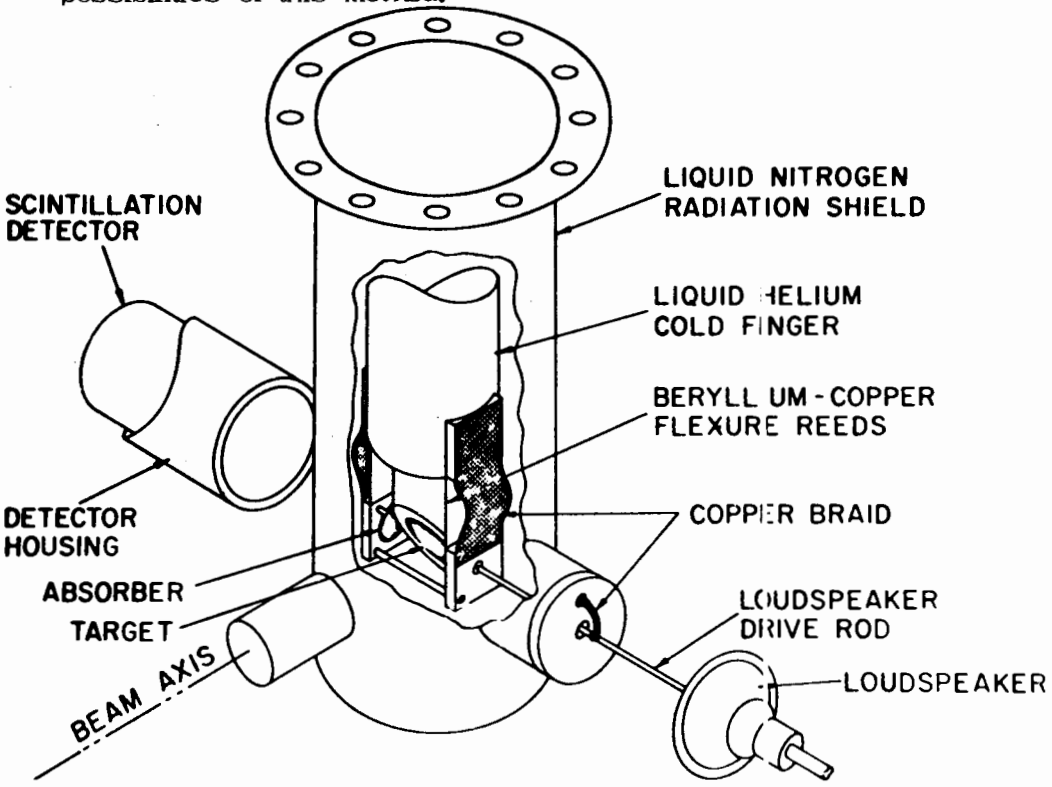

Fig.3. Schematic diagram of the liquid helium kryostat used for the Mössbauer effect studies in Coulomb excitation[6].

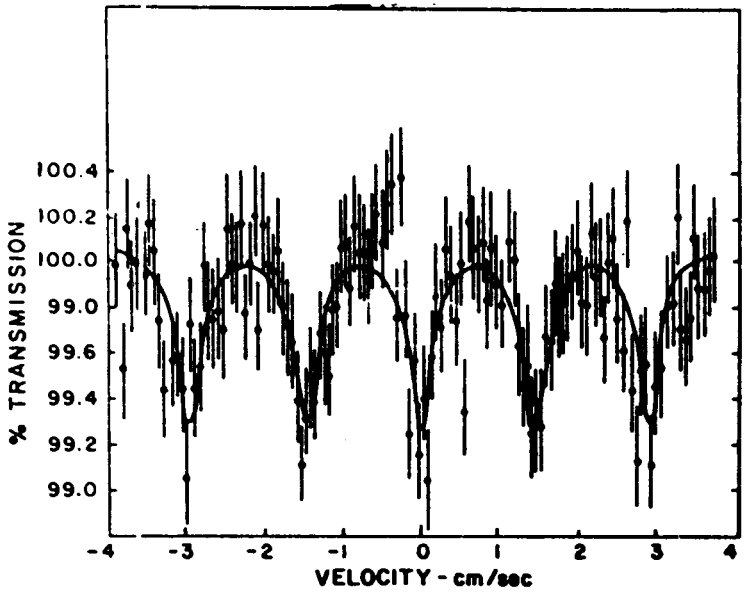

Fig.4. Mössbauer absorption spectrum following Coulomb excitation of the first 2^+ state in ^{176}Yb /6/.

Fig. 3 shows a liquid helium kryostat, used by Lee et al./6/, for the Mössbauer effect studies in Coulomb excitation. In Fig.4 their Mössbauer absorption spectrum following Coulomb excitation of the first 2^+ state in ^{176}Yb , obtained with ^{176}Yb metallic target and $^{176}YbCl_3\,6H_2O$ absorber, is shown.

What are the limitations of the Mössbauer method?

1. Its application is limited to nuclei for which the Mössbauer effect can be observed. They should be stable or at least long-lived, as the absorbers have to be prepared from the same isotope. Measurements can be performed for the excited states lower than ca. 150 keV, otherwise the probability of the recoil-less emission and absorption becomes negligibly small.

2. The limit for accessible life-times is related to the natural line-width of the investigated transition. Zeeman splitting should be at least of the same order of magnitude as the natural line-width Γ . It means that

$$\Delta E = g\mu_N H \geq \Gamma = \frac{\hbar}{\tau},$$

hence

$$\tau \geq \frac{\hbar}{g\mu_N H} .$$

Using a typical g -value of 0.5 we obtain

$$\tau \geq \frac{4{,}2 \cdot 10^{-4}}{H(G)} \text{ s} .$$

This shows that even for very high internal magnetic fields of several megagauss measurements cannot be performed for life-times shorted than ca. 10^{-10} s.

On the long life-times side, the limitation is due to the technical difficulties in observation of very narrow lines. E.g. for $\tau = 10^{-6}$ s and for a transition energy of 50 keV the line width corresponds to the Doppler velocity of 7,5 μ/s.

2.2. Method of Perturbed Angular Correlations

Starting the discussion of the method of perturbed angular correlations I shall remind you of the basic ideas of the angular correlation of a gamma-gamma cascade. We are dealing with two successive gamma transitions γ_1 , and γ_2 of multipolarities L_1 and L_2 , going from the initial state with the spin value I_1 , through the intermediate state I, to the final state I_f. (Fig. 5a). The relative probability that γ_2 is emitted into the solid angle $d\Omega$

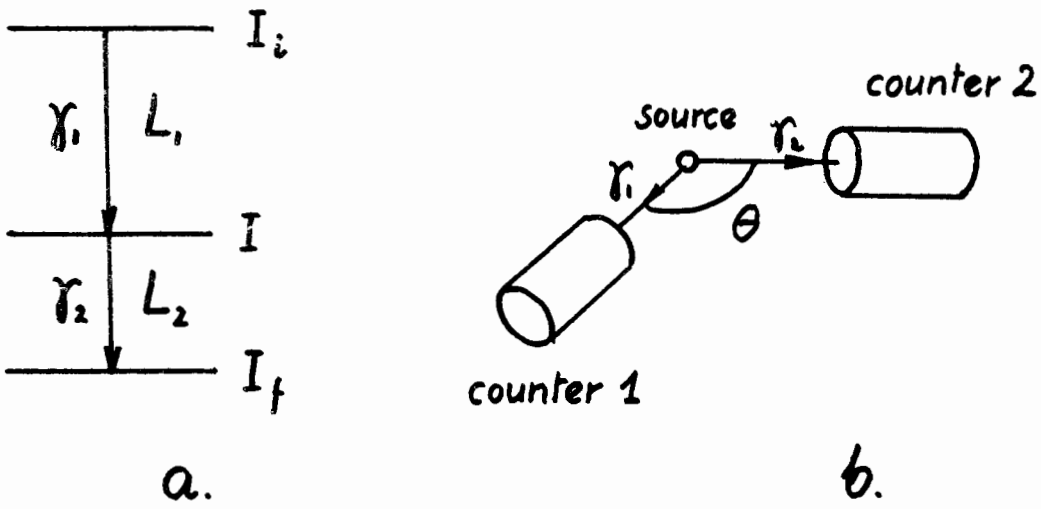

Fig.5. a) Gamma-gamma cascade.
b) Position of counters in angular correlation measurements.

at an angle θ with respect to the direction of γ_1 is expressed by $W(\theta)d\Omega$ where the angular correlation function $W(\theta)$ is given by

$$W(\theta) = 1 + \sum_{k=2}^{k_{max}} A_k P_k(\cos\theta).$$

A_k are the angular correlation coefficients, depending on the spin values of the involved nuclear levels and on the multipolarity of γ transitions. $P_k(\cos\theta)$ are Legendre polynomials. The summation index k is an even integer and , for pure multipole radiation, fulfils the selection rule

$$0 \leq k \leq \text{Min}(2I, 2L_1, 2L_2).$$

For $I=0,1/2$, $W(\theta)=1$, that means that the directional distribution of gamma rays is isotropic. $k_{max}=6$ is never encountered in practice as this case demands $l \geq 3$ and at least the octupole character of both transitions.

During the life-time of the intermediate state, the interaction of nuclear moments μ or Q with extranuclear magnetic fields or with electric field gradients may change the population of nuclear sublevels, which leads to the perturbation of the angular correlation. The study of these perturbations yield important information on the internal fields acting on nuclei in different substances. On the other hand, using known interacting fields, it is possible to deduce nuclear moments from the observed effect of perturbation. For measurements of nuclear magnetic moments the perturbation of an angular correlation, by an oriented magnetic field of the known intensity, has to be studied.

To discuss the effect of a magnetic field on an angular correlation it is convenient to use a slightly different form of the correlation function:

$$W(\theta) = 1 + b_2 \cos 2\theta + b_4 \cos 4\theta .$$

The new coefficients b_k can easily be expressed by A_k. In a magnetic field H, perpendicular to the γ-γ observation plane, the angular correlation function becomes time-dependent and takes the form

$$W(\theta, \pm H, t) = 1 + b_2 \cos 2(\theta \mp \omega t) + b_4 \cos 4(\theta \mp \omega t).$$

The experiments are performed with two counters working in coincidence. Then the angle θ is the angle between directions from the source to the counters (Fig.5b).

We have to distinguish the two cases as follows:

1. The life-time τ of the investigated intermediate state is longer than the resolving time τ_0 of the coincidence circuit $\tau \geq \tau_0$ and 2. the opposite case, when

$$\tau < \tau_0 .$$

In the first case it is possible to study the time-dependence of the angular correlation in a magnetic field. The coincidence rates $N(\theta, \pm H, t)$ for an angle θ between counters and for two opposite directions of the magnetic field can be expressed in the following way

$$N(\theta, \pm H, t) \sim e^{-t/\tau} \; W(\theta, \pm H, t) ,$$

where the factor $e^{-t/\tau}$ describes the exponential decay of the intermediate state.

Using the time-to-pulse-height converter and a multichannel analyzer it is possible to display the function $N(\theta, \pm H, t)$. The block diagram of a typical arrangement is shown in Fig.6. For $\theta = 135^{\circ}$ the angular correlation function becomes very simple

$$W(135^{\circ}, \pm H\, t) = 1 \mp b_2 \sin 2\omega t - b_4 \cos 4\omega t .$$

Fig.7a shows the shape of the time-dependence of the coincidence rates $N^{\pm}(t) = N(135^{\circ}, \pm H, t)$. This is the decay curve of the intermediate state modulated by Larmor precession in the magnetic field. It is convenient to calculate the following expression

$$R(t) = \frac{N^{+}(t) - N^{-}(t)}{N^{+}(t) + N^{-}(t)} = \frac{b_2 \sin 2\omega t}{1 - b_4 \cos 4\omega t} .$$

When $b_4 = 0$, $R(t)$ has the form of a sinus curve with the period two times shorter than the Larmor precession period. When b_4 is present, the b_4 term in the denominator modifies the shape of $R(t)$

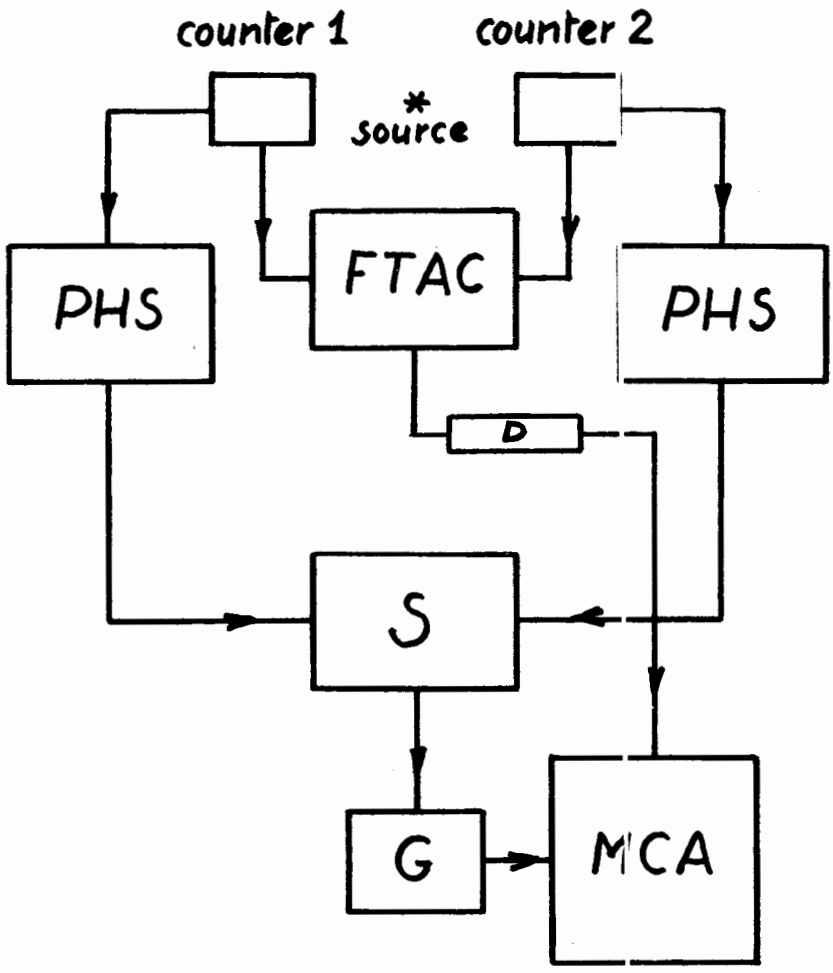

Fig.6. Block diagram of the typical set-up for measuring the time-dependence of the angular correlation.
PHS - pulse hight selectors, FTAC - fast time-to-amplitude converter, S - slow coincidence circuit, G - gate, D -delay, MCA - multichannel analyzer. For sake of simplicity preamplifiers and amplifiers are not shown.

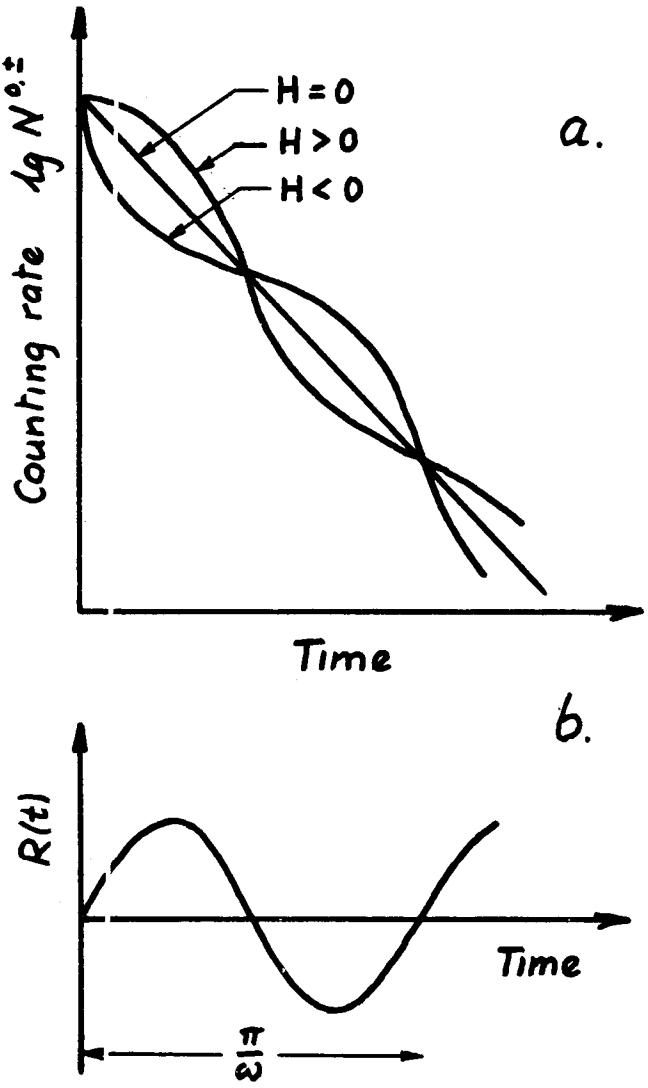

Fig.7. a) Time-dependence of the coincidence rates $N(135^{\circ}, \pm H, t)$.
b) Spin precession curve $R(t)$.

but zero-crossing points and hence the measured period remain unchanged. To determine ω we need not know either the life-time of the intermediate state or the angular correlation coefficients b_k. Of course, the larger the correlation coefficients, the higher the amplitude of the precession curve and the better the accuracy can be achieved with the same counting statistics.

Using the perturbed angular correlation method we have to avoid any additional perturbation of the angular correlation caused by the quadrupole interaction in the intermediate state. We have to work either with solid sources with a cubic crystalline lattice, in which no gradient of the electric field is present, or with liquid sources of low viscosity, in which local gradients average to zero due to the fast molecular movements. The spin precession method described above has the great advantage that the presence of a weak quadrupole interaction does not effect the determination of ω. Such an interaction results in the damping of the precession curve but again the zero-crossing points determining the precession period remain unchanged.

The spin precession method was for the first time applied in MIT to the magnetic moment measurement for the 6 ns, 81 keV state in ^{133}Cs by Deutsch and myself[7,8] in 1959.

In 1961 another version of the spin precession method has been developed. Taking independent measurements for two angles between counters

$$\theta_1 = \frac{5}{8}\pi = 112.5^\circ \qquad \text{and} \qquad \theta_2 = \frac{7}{8}\pi = 157.5^\circ$$

and for two opposite directions of the magnetic field $\pm H$ the following combination of the time-dependent counting rates can be formed

$$F(t) = \frac{N_1^+ - N_1^- + N_2^+ - N_2^-}{N_2^+ - N_1^+ + N_2^- - N_1^-} = tg\,2\omega t\,.$$

Results for the 15 ns, 482 keV state of ^{181}Ta, obtained in Cracow by Bozek et al.[9], are shown in Fig.8. Each point of the experi-

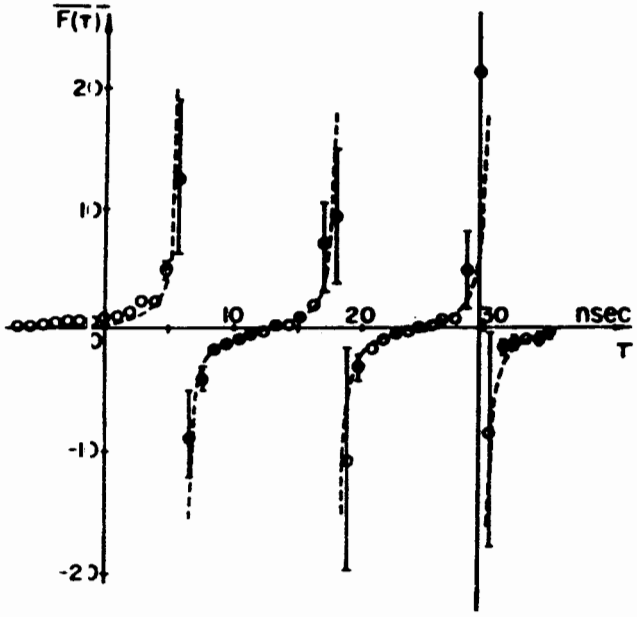

Fig.8. The ratio F(t) for the cascade of 133 -482 keV in ^{181}Ta in the external magnetic field of 21 kG.

mental tangent curve can be used for the independent determination of ω. Our result of $g = 1.336\ (15)$ was until recently the most accurate g-factor value obtained with the PAC method.

When the life-time of the investigated state is shorter than the resolving time of the fast coincidence circuit ($\tau < \tau_0$) the integral effect of the rotation of the angular correlation pattern has to be measured. The integral angular correlation function is given by the formula

$$\overline{W(\theta, \pm H)} = \frac{1}{\tau} \int_0^{\tau_0} e^{-t/\tau} W(\theta, \pm H, t)\, dt .$$

If τ_0 is several times longer than τ, the upper integration limit might be replaced by infinity and we obtain

$$\overline{W(\theta, \pm H)} = 1 + \sum_k \frac{b_k}{\sqrt{1 + (k\omega\tau)^2}} \cos k(\theta \mp \Delta\theta_k),$$

where

$$\Delta\theta_k = \frac{1}{k} \operatorname{arctg} k\omega\tau .$$

It is easy to see that two effects are present, i.e. the attenuation of the angular correlation expressed by the denominator $\frac{1}{\sqrt{1 + (k\omega\tau)^2}}$ and the rotation given by $\Delta\theta_k$. When $|\omega\tau| \ll 1$ the higher powers of $\omega\tau$ can be neglected and the measurement for $\theta = 135^\circ$ and for two opposite directions of the magnetic field gives

$$R = \frac{N^+ - N^-}{N^+ + N^-} = - \frac{2 b_2 \omega\tau}{1 - b_4} .$$

In order to calculate ω from the experimentally determined value of R the angular correlation coefficients b_2 and b_4 and the life-time τ of the investigated state should be known. For larger $\omega\tau$ it is better to measure the integral correlation function for several different angles and to determine its shift caused by the applied magnetic field. Hence $\omega\tau$ should be calculated using the exact formula.

The integral PAC method was used for the first time in Zürich by Aeppli et al.[10] in 1952. An example of its more recent application is given in Fig.9 taken from the work by Karlsson et al.[11].

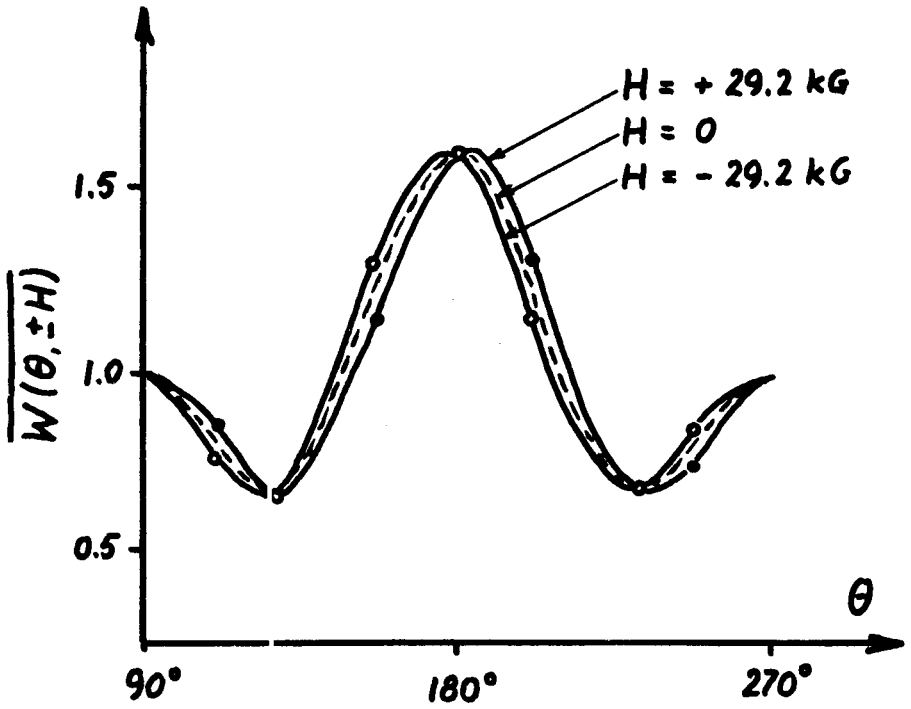

Fig.9. Angular displacement of the integral $\gamma-\gamma$ directional correlation of ^{188}Os in a transverse magnetic field[11].

The integral PAC method may be subject to errors if the quadrupole interaction in the intermediate state is present. The resulting attenuation of the angular correlation reduces the angle of rotation, and in order to take care of this effect, the attenuation factors should be determined in additional experiments.

The question arises what are the limiting factors for this kind of measurements and how to push down the lower limit of lifetimes of excited states for which the g -factor determination can be performed. For very small $\omega\tau$ values the main source of errors lies in the statistics of the coincidence counting. This may be illustrated by the following example. Let us take a rather favourable case of $b_2 = 0.1$ which corresponds to 20% anizotropy of the angular correlation and assume a typical coincidence counting rate of 20 pulses per second. Then one week of coincidence counting is needed to measure $\omega\tau = 10^{-2}$ with the statistical error of 20%. In order to reduce the error to 5% we need 4 months of continuous counting. It seems rather hopeless to attempt measurements of $\omega\tau$ smaller than 10^{-2} with a reasonable accuracy. What does it mean in terms of the life-time? We obtain

$$\tau = \frac{10^{-2}}{\omega} = \frac{2.1 \cdot 10^{-6}}{gH}$$

and for a typical value of $g = 0.5$

$$\tau = \frac{4 \cdot 10^{-6}}{H}.$$

It is obvious that the limiting factor is an available intensity of the magnetic field. With $H = 65$ kG, which is the magnetic field of large electromagnets used for g -factor measurements the τ limit will be ca. 10^{-10} s. It is possible to improve, somehow, the si-

tuation by the application of a multicounter arrangement. When the experimental set up consists of three counters instead of two, simultaneous measurements for two angles can be performed and the counting statistics is improved by a factor of two. It does not make, however, any drastical difference. The only and really efficient way is to increase the magnetic field intensity. One can think of using superconducting coils to produce fields three or four times higher, but a much better and simpler way is to use very large magnetic fields acting on nuclei in ferromagnetic materials.

The interest in the internal magnetic fields, aroused mainly by the Mössbauer effect studies, is growing very rapidly. For the time being, the internal fields acting on nuclei embeded in an iron lattice are determined for more than 50 nuclear species[12]. Table 1 gives some examples of magnetic fields acting in iron. Using these fields it is possible to measure g-factors for nuclear states in a picosecond range. The orientation of internal fields can be achieved by an external magnetizing field. A few hundred gauss are usually sufficient to saturate a ferromagnetic foil with implanted nuclei under investigation.

Different implantation techniques are used:

1. Formation of an alloy with a ferromagnetic metal by melting.
2. Thermal diffusion into a ferromagnetic host.
3. Implantation with a mass separator.
4. Implantation of excited nuclei recoiling from nuclear reaction, Coulomb excitation or radiactive decay.

The first two methods generally give well defined and reproducible internal fields, but they can be used only for relatively long-lived parent isotopes. The lower limit of life-times depends on the time needed for the annealing process. Moreover, they do not

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Table 1.

Hyperfine Fields for Impurities in Fe

Element	Temperature °K	Hyperfine field kOe
Al	1.4	- 55(1)
Mn	0	- 226.97
Fe	0	- 336.9
Cu	273	- 212.7
Rh	0	559.6(16)
Ag	0	- 282(20)
Sn	100	- 81(4)
Sb	He	+ 231(6)
Sm	R	+ 1400(160)
Dy	R	- 2000(300)
Ta	He	- 656(13)
W	He	- 643(13)
Os	He	1130(23)
Pt	He	- 1280(26)
Hg	R	- 980(180)
Pb	R	+ 262(20)

He - liquid helium temperature, R - room temperature.

work for rare earth nuclei, reasons for this not being, up to now, completely understood.

The mass separator technique seems to give unique internal fields even for rare earths. In order to obtain sufficiently large penetration depth the separator beam energy should be higher than ca. 40 keV. This method of implantation can be applied to radioactive sources living for much shorter periods than those accessible by the annealing methods and with a mass separator working in the accelerator beam it will be possible to perform measurements for parent activities living for less than one second.

The implantation by nuclear recoil makes it possible to measure g-factors for excited states produced in nuclear reactions or by the Coulomb excitation. Recent experiments by Grodzins[13] showed, however, that this method of implantation should be applied with certain caution. He proved that the internal magnetic fields acting on a recoiling nucleus in a ferromagnetic host change in time. It is probably due to the Coulomb attraction of polarized electrons by highly ionized atom, moving through the magnetized foil, which changes considerably the density of polarized electrons at the nucleus. The appearance of transient anomalous magnetic fields explains the discrepances of results obtained by different authors, using this technique. The discrepances are especially marked in the case of life-times in a picosecond range where the anomalous fields play an important role. On the other hand, the future application of transient fields of high intensity will offer new possibilities of g-factor measurements for very short-lived excited states.

3. Methods Based on the Radioactive Detection of Nuclear Magnetic Resonance (RD-NMR)

The conventional methods of magnetic moment measurements mentioned at the beginning of this lecture can hardly be used for nuclear states living shorter than a few minutes. On the other hand, pure nuclear techniques fail for life-times longer than ca. 10^{-6} s. The broad intermediate region of isomeric nuclear states is practically unexplored.

Methods based on the radioactive detection of nuclear magnetic resonance seem to be appropriate to fill this gap. They consist in radiofrequency irradiation of a nuclear sample, in which the magnetic substates of a radioactive level are unequally populated, and in the observation of NMR absorption through the frequency dependence of a counting rate. These methods combine high accuracy of resonance frequency measurements and high sensitivity of nuclear techniques. Their accuracy depends on the resonance line width, which is determined either by the life-time of the investigated nuclear state or by the spin-lattice relaxation time.

The RD-NMR method was used for the first time in 1952 by Deutsch and Brown[14] in their experiments on the hyperfine structure of positronium. In 1959, it was applied by Connor[15] for the magnetic moment measurement for the 0.8 s ground state of ^{8}Li, produced by capture of polarized neutrons.

The recent development of various versions of the RD-NMR method was encouraged by the discovery of the hyperline enhancement of the radiofrequency field. For RD-NMR experiments the rf field should be sufficiently large to make the transition probability between the magnetic sublevels comparable to the decay probability of the excited state. It seemed impossible to meet

power requirements for short-lived nuclear states accessible by the PAC and Mössbauer methods. Only in 1965 [16] it was realized that the magnetic field amplitude H_1 of the rf field at the nucleus is stronger than the applied field H_1^{app} by the enhancement factor $F = 1 + \frac{H_{hf}}{H_0^{app}}$, where H_{hf} is the hyperfine field at the nucleus, and H_0^{app} is the applied static field. Due to this enhancement a very low rf power is needed to observe NMR for short-lived nuclei embeded in ferromagnetic substances.

The following techniques can be used for the radioactive detection of nuclear magnetic resonance:

1. Angular correlation of gamma rays (NMR-PAC). The accessible life-time range of intermediate states is $10^{-8}s < \tau < 10^{-5}s$.
2. Asymmetry of β emission from radioactive ground states or isomeric states and angular distribution of gamma rays from isomeric states, populated in nuclear reactions (NMR-NR). The life-time range $10^{-8}s < \tau < 10^{-2}s$ can be explored.
3. Anizotropy of gamma rays or asymmetry of β emission for oriented nuclei (NMR-NO). In this case the life-time of the investigated state should be sufficiently long to permit the reorientation process, which means that the condition $\tau \gtrsim T_1$, where T_1 is the nuclear spin-lattice relaxation time, should be fulfilled.
4. Mössbauer effect in the life-time range $\tau > 10^{-8}s$ (NMR-ME).

In order to illustrate the RD-NMR methods I shall describe briefly the three recent experiments reported at the Asilomar Conference on Hyperfine Interactions Detected by Nuclear Radiation, 1967.

Matthias et al.[17] applied the PAC-NMR method to the 235 ns, 75 keV state in ^{100}Rh, using the 84 keV - 75 keV gamma cascade. The radioactive source was prepared by diffusing car-

rier-free ^{100}Pd parent into an iron foil of ca. 1 μ thickness. The foil was mounted in a rf coil, perpendicular to the static magnetic field produced by two d.c. coils (Fig.10). The polarizing field of ca.

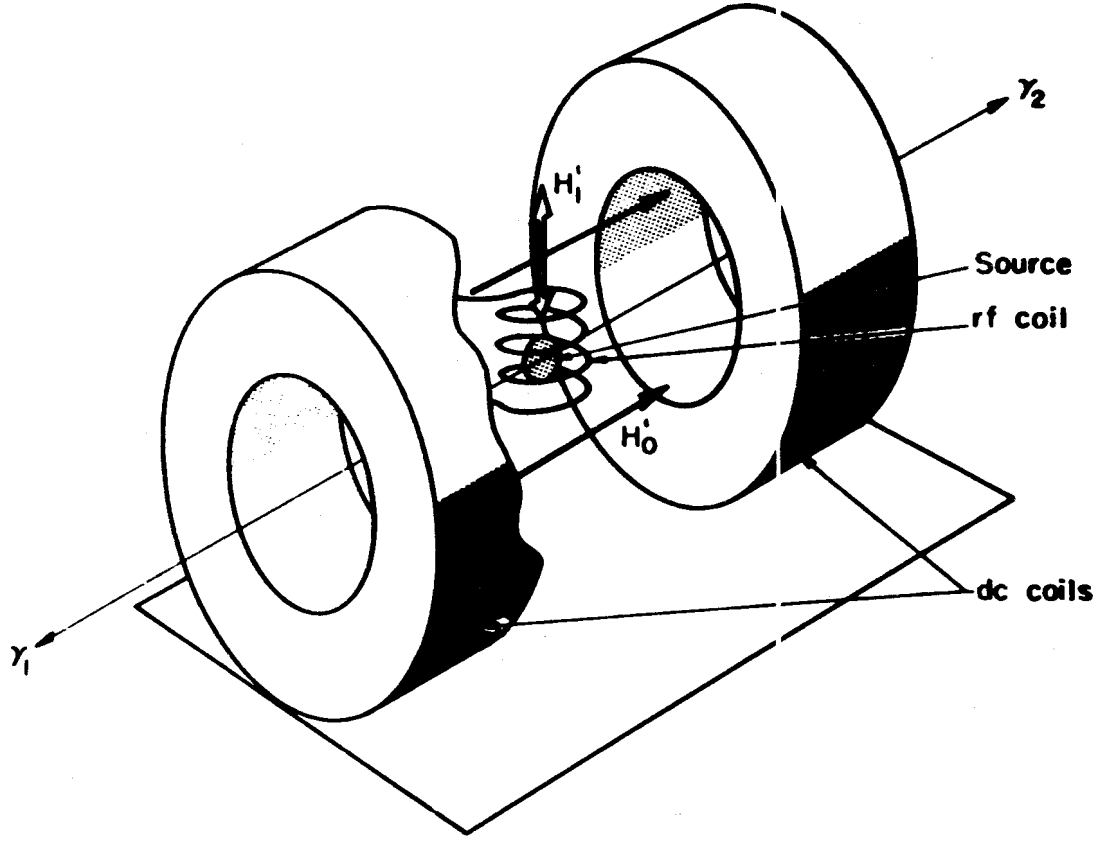

Fig.10. Geometry of the RAC-NMR experiment[17].

400 G was sufficient to saturate the foil. Two NaI(Tl) detectors, working in coincidence, were placed at $\theta = 180^{C}$. The frequency dependence of the coincidence counting rate is shown in Fig.11.

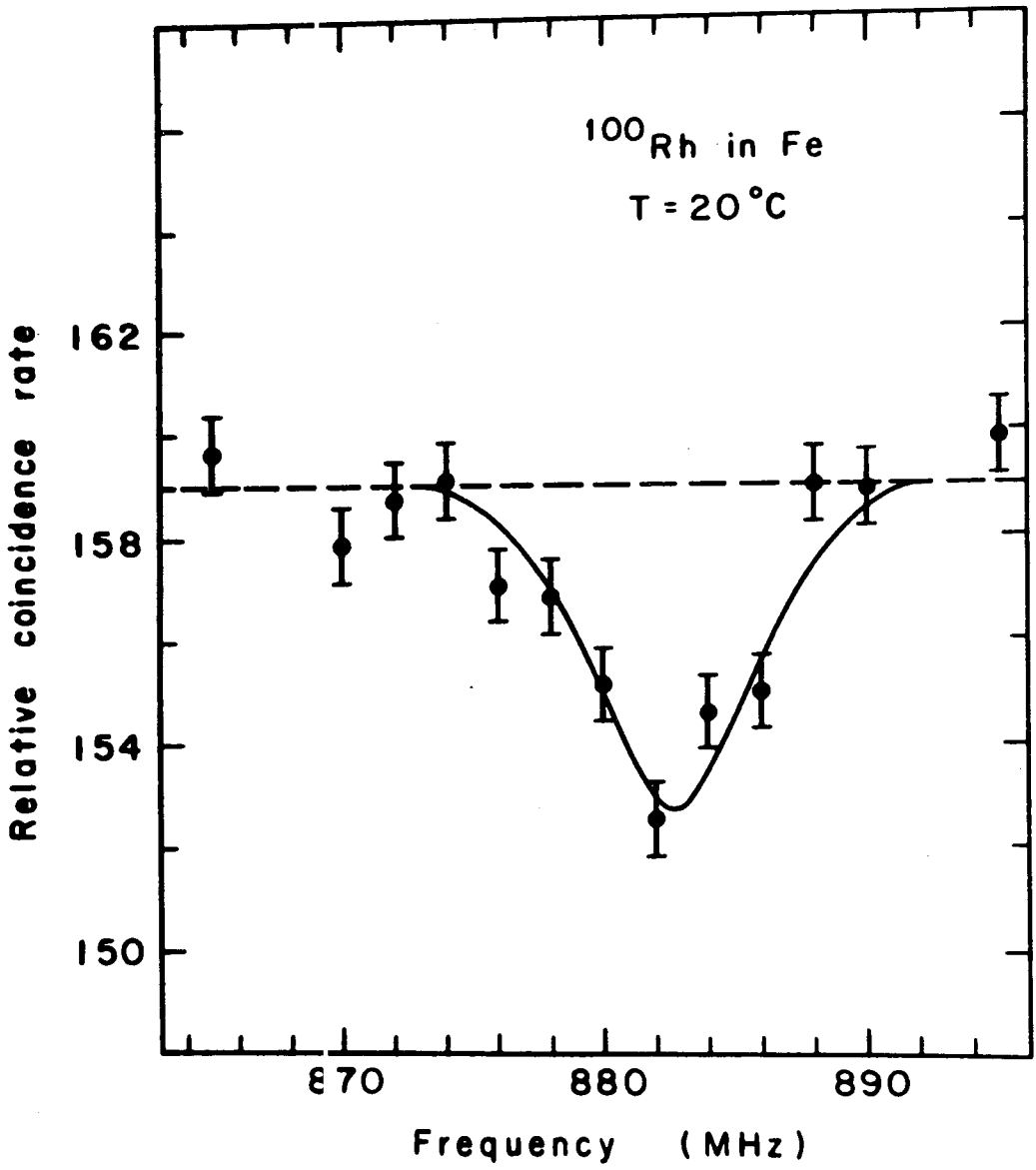

Fig.11. Resonance effect for the 75 keV, 235 ns state of ^{100}Rh /17/.

For the resonance destruction of the angular correlation, at 882.7± 2.0 MHz , the average rf power of 80 W was sufficient, the enhancement factor of the rf field being of the order of 10^3. Using the known value of the g -factor of the investigated state g = 2.15 the hyperfine field acting at room temperature on Rh nuclei in Fe H_{hf} = 538·0.(6) kG was found.

The magnetic moment measurement for 20 ms ground state of ^{12}B performed by Sugimoto /18/ illustrates the application of the NMR-NR method. Recoiling nuclei of ^{12}B ejected from a thin boron target in the ^{11}B(d, p)^{12}B reaction were captured by a metal catcher foil at the definite reaction angle. The polarization of ^{12}B nuclei, normal to the reaction plane, was preserved due to a static magnetic field, of a few kG, parallel to the polarization direction and due to the proper choice of stopping materials. The asymmetry of β emission was measured with two Si(Li) detectors. At the rigth frequency of a rf field produced in the coils perpendicular to the static field, the resonance destruction of nuclear polarization takes place and the β asymmetry decreases. Fig.12 shows the Sugimoto results obtained for different catcher foils. The uncertainty of the final result μ = 1.003± 0.001 nm is due to the Knight shift in metals used as the catcher foils. It cannot be estimated reliably because of the lack of knowledge of electronic states of boron in metals.

The g -factor measurement for the 2.7 year ground state of ^{125}Sb by Barclay et al./19/ serves as an example of the application of the NMR-NO method. ^{125}Sb in iron foil was cooled by the adiabatic demagnetization of chromium alum to about 0.015 K°. Nuclear polarization was attained by using a superconducting Helmholtz coils. The rf field of 0.5 mG amplitude was produced by a coil perpendicular to the polarizing field. The angular distri-

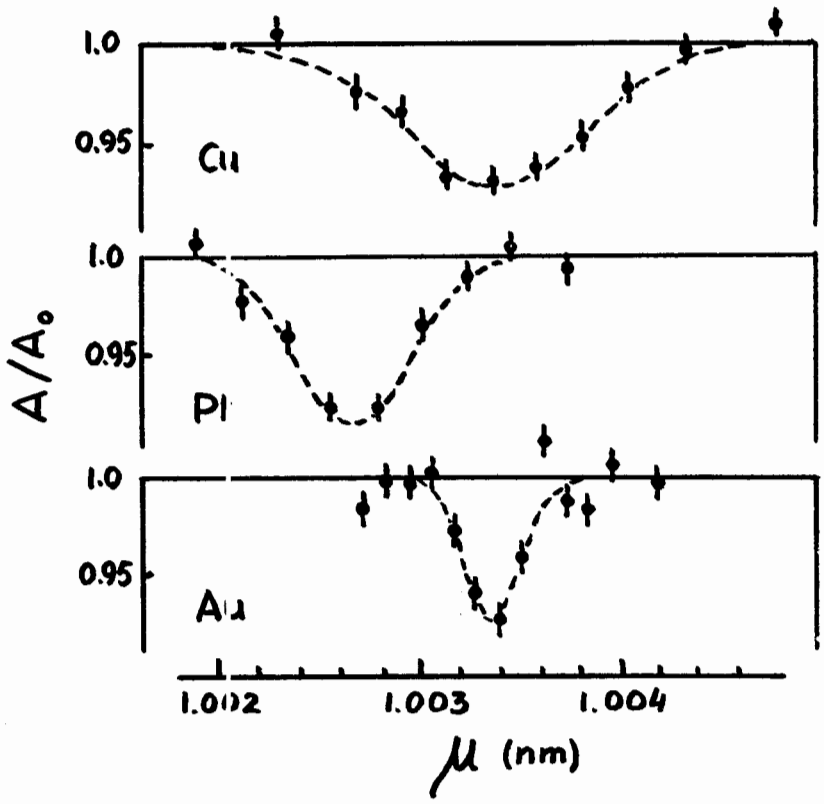

Fig.12. Resonance determination of the magnetic moment of ^{12}B implanted in different materials [18].

bution of the 462 keV gamma transition in the daughter ^{125}Te nuclei was used for the indication of the resonance destruction of the nuclear orientation of ^{125}Sb . Fig.13 shows the results. Resonance frequency measurements for different polarizing fields H_0 gave the straight line (Fig.14) described by the relation

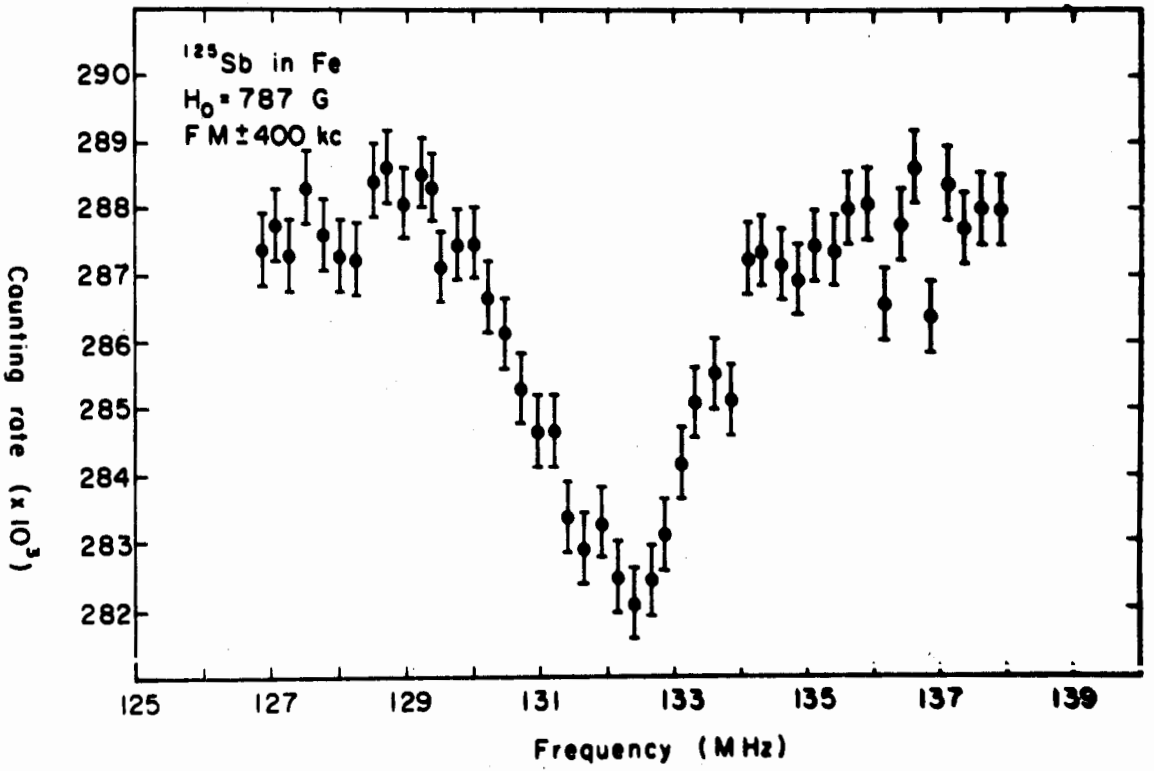

Fig.13. Resonance for ^{125}Sb in iron. ν_R = 132.15(10) MHz .

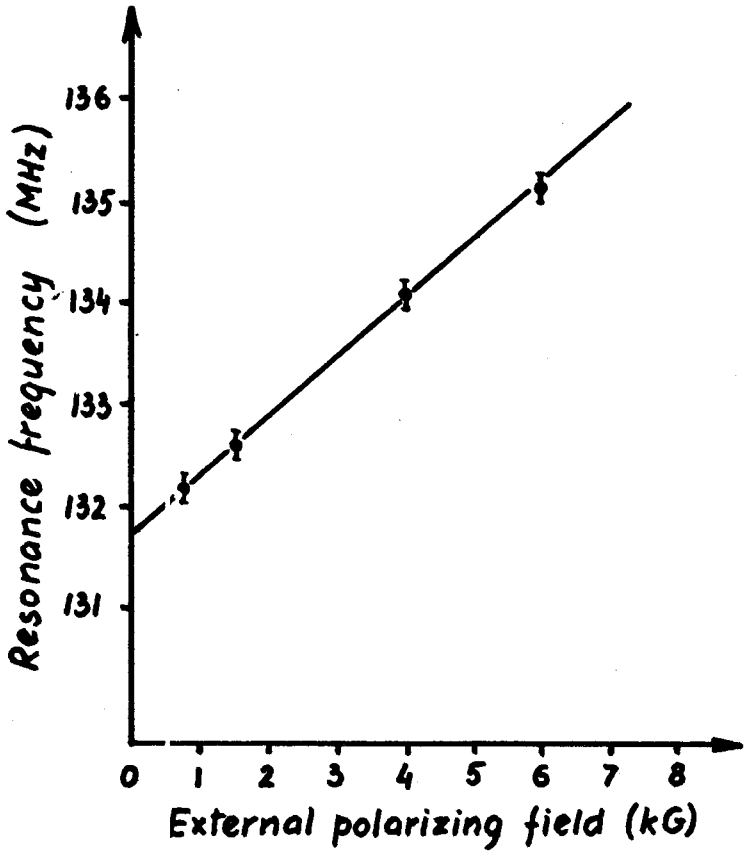

Fig.14. Shift of the resonance frequency with external polarizing field [19].

$$\nu_R = \frac{\mu_N}{\hbar} g(H_{hf} + H_0).$$

The slope of this line gives the g -factor value

$$|g| = 0.748 \pm 0.018$$

and, with the g -factor known, the intersection with the frequency axis yields

$$H_{hf} = +231 \pm 6 \text{ kG} .$$

Concluding Remarks

Magnetic moment measurements for excited nuclear states, coming from M.Deutsch's γ-γ angular correlation work of 1948 and promoted by Mössbauer's discovery of 1958, became a very broad and exciting field of investigations. The methods used nowadays go far beyond the scope of nuclear physics. They involve atomic physics, solid state physics, chemistry and low-temperature techniques.

The application of internal magnetic fields makes it possible to perform measurements in a picosecond range and the discovery of very high transient fields acting on the nuclei recoiling through a ferromagnetic host gives hope that even shorter life times will be attacked in the near future.

The experiments in the accelerator beams have opened a new field of investigation involving short-lived isotopes produced in nuclear reaction.

Different combinations of nuclear techniques with the nuclear magnetic resonance will make it possible to cover a broad range of, hitherto unaccessible, isomeric states.

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