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ABSTRACT

Digital analysis of perturbed angular correlations (DAPAC) is described. Fourier analysis and autocorrelation of data from a 1 GHz digital time-to-height converter render feasible precise g-factor determinations of millisecond states. For the ^{100}Rh .235- μsec 74.2-keV state, $g = 2.151 \pm .004$.

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Perturbed angular correlation measurements have been widely used to determine magnetic moments of short-lived excited nuclear states¹⁾, and systematic information has been gathered for example for g_R -factors of the first excited rotational states in deformed nuclei. In a few cases this technique has also been applied to the investigation of hyperfine fields of impurities in magnetic host lattices^{2,3,4)}. The convenient and simple set up, especially in the random field method, render this technique very useful in particular for measurements of the temperature dependence of induced hyperfine fields⁵⁾.

It is recognized that for half-lives long enough to employ the time-differential method, good accuracy, of the order of a percent, can be obtained. The precision with which interaction frequencies can be measured improves with increasing half-life. Surprisingly enough, however, there has not yet been one measurement on a state with a half-life larger than 500 nsec. It has been suggested⁴⁾ that attenuating internal perturbations can be avoided by incorporating the isotope into a cubic, "non-magnetic" metal lattice. In fact, measurements⁶⁾ on ¹⁰⁰Rh in metallic sources prove that up to 2 μ sec, no attenuation of the angular correlation pattern is detectable. The important remaining perturbation for nuclei that have retained their spin orientation information for 2 μ sec in such a lattice is their coupling to the spin magnetic moments of the conduction electrons. It is known, however, that relaxation times, T_1 , in metals are given by $T_1 \cdot T \approx 10^{-2}$ sec $^{\circ}$ K for heavy elements, increasing to $T_1 \cdot T \approx 1$ sec $^{\circ}$ K for lighter elements. Consequently, T_1 alone provides the theoretical upper limit for perturbed angular correlations measurements in cubic metals. The time-dependent angular correlation pattern, which is the Fourier transform of the NMR line shape, provides an interesting alternative method for determining T_1 .

Until now there has been no method for measuring magnetic moments of isomeric states with half-lives between 10^{-6} sec and 1 sec. It is our concern to develop an experimental technique which allows the application of the perturbed angular correlation method up at least to the millisecond range. Although only a limited number of states with lifetimes in this range are known to be populated by cascading radioactive decay, many more isomeric levels can be conveniently produced by nuclear reactions. The generally non-isotropic angular distribution of gamma rays following the reaction process could be used for time-differential measurements, provided the beam pulses are sufficiently short not to destroy the coherence. This principle has been used^{7,8,9)} in case of the 198 keV level in ^{19}F , which has a half-life of 87 nsec. But it has not yet been applied to longer half-lives.

When trying to use the conventional time-differential method on half-lives longer than 1 μsec , one runs into the following basic difficulties: a) the source strength has to be reduced to keep the ratio of true to accidental coincidences acceptable; b) the time resolution of analog converters is limited and of the order 1% of the total time range; c) the limited time resolution requires the use of low magnetic fields. In addition one has the usual problems with linearity, stability, and, in most instances, a memory limitation in the analyser.

It is the purpose of this letter to present another experimental approach which overcomes all the above weaknesses of the conventional technique except the ratio of true to accidental coincidences. The idea is to obtain the data directly in a digital form and to find the interaction frequency by calculating the Fourier transform of the time-spectrum.

The use of a digital time-to-height converter offers automatically the advantages¹⁰⁾ that the resolving time is independent of the time range used, and that there is practically no limitation in channel numbers, it has perfect linearity and a much greater stability than analog systems. Further, the necessity of an accurate time calibration is completely avoided. In our case a digital time-to-height converter with a crystal-stabilized 1000 Mc/sec driving frequency was used¹¹⁾. The Eldorado model 793 1 nsec time interval counter provides this together with a 9 decade scaler which allowed the use of the whole time range between 10^{-9} sec and 1 sec, or any desired part of it. The numbers occurring in the scaler and representing the time interval elapsed between γ_1 and γ_2 were dumped via a Kennedy 1500/5 incremental tape unit onto an IBM-compatible magnetic tape. The data on the tape were later put in order and analysed by the computer¹¹⁾.

The data analysis is based on the fact that the Fourier transform of the time spectrum $W(t)$ is a function of frequency, $f(\nu)$, with the resonance frequency given by $\nu_L = 2gH \frac{\mu_N}{h}$. After normalization for the exponential decay the time spectrum can be described by the function $W(t) = \sum_k A_k P_k (\cos(\theta_0 \pm \omega_L t))$ for the case of an oriented magnetic dipole interaction. The even and odd parts of the Fourier transform are calculated separately,

$$A(\nu) = \int_{T_{\min}}^{T_{\max}} W(t) \sin 2\pi \nu t \, dt, \quad B(\nu) = \int_{T_{\min}}^{T_{\max}} W(t) \cos 2\pi \nu t \, dt,$$

and the absolute value

$$F(\nu) = \left[A(\nu)^2 + B(\nu)^2 \right]^{1/2}$$

is formed. The Fourier transform is usually calculated in frequency steps of $\left[2(T_{\max} - T_{\min})\right]^{-1}$ but smaller steps can be used. The phase of the Fourier transform is defined as

$$\phi(\nu) = \tan^{-1} \left[\frac{-A(\nu)}{B(\nu)} \right] .$$

and is chosen in accordance with the normal sign convention of the Fourier transform. In table I the expected phases for the most common detector geometries and field directions are summarized.

An alternative way of treating the data is to use the autocorrelation function

$$\frac{C(\tau)}{C(0)} = \frac{\text{ave} \{ [W(t) - \bar{W}] [W(t+\tau) - \bar{W}] \}}{\text{ave} \{ [W(t) - \bar{W}] [W(t) - \bar{W}] \}}$$

in the Fourier transform

$$G(\nu) = \int_0^{\tau_{\max}} \frac{C(\tau)}{C(0)} \cos 2\pi\nu\tau \, d\tau .$$

Here, τ is the lag at which the data are correlated. This autocorrelation technique smoothes the discrete data carrying a statistical uncertainty at each point. Consequently, the peak-to-noise ratio is more than an order of magnitude better than that obtained by the simple Fourier transform of the data. Thus the autocorrelation technique is extremely powerful for the analysis of small amplitude modulations. The application of this analysis, however, is limited by the maximum possible lag τ , which is about $1/3$ of the total number of channels used. The frequency steps are given by $(2 \tau_{\max})^{-1}$ which means that for shorter half-lives

the frequency scale is too insensitive and the resonance is determined by too few points. This is actually the case in the following example.

A measurement of the g factor of the 74.8 keV level in ^{100}Rh will serve to demonstrate the method of digital analysis of perturbed angular correlations (DAPAC). With a half-life of $T_{1/2} = 235$ nsec, a g factor of $g = +2.15$, and an anisotropy of $A = +30\%$, the 84-74.8 keV cascade is a favorable test case⁶⁾. Both the 84 keV and 74.8 keV gamma rays were measured with Ge(Li)-detectors. Delay gates were used to energy-select the fast pulses which then directly served as "start" and "stop" pulses for the time interval counter. After ordering the numbers from the magnetic tape we get the usual time spectrum modulated by the rotation of the angular correlation pattern in the external magnetic field. In fig. 1 the Fourier transforms of the data, $F(\nu)$, and of the autocorrelations coefficient, $G(\nu)$, are shown for a measurement in a field of 4996 Gauss. The phase is $\phi = \pi/2$ in this case, in agreement with what is to be expected for $\gamma_1(135^\circ\text{cw})\gamma_2$, field up, a positive anisotropy and a positive g -factor, according to table I.

Some more measurements were carried out with the test sample of ^{100}Rh in Rh-metal. The results of all runs are listed in table II. The resonance frequency was obtained from the derivative of the resonance peak, which is given by either the cosine or the sine transform, depending on the geometry of the experiment. This procedure is demonstrated in fig. 2. The absolute function $F(\nu)$ often gives an erroneous frequency as the derivative is not necessarily symmetric around zero. From the resonance frequency, ν_L , the g -factor can be calculated using the relations $g = \frac{h}{2\mu_N} \frac{\nu_L}{H}$. In spite of the much better peak-to-background ratio we did not make any use of the Fourier transform of the autocorrelation function, because the resonance was given by too few points. The error in the frequency was defined as the reading error of the inflection point

of that transform which represents the derivative. The individual results summarized in table II are in good agreement within the limits of error and reflect clearly the degree of accuracy one can obtain with this method. As a final result for the apparent g-factor we give the average value of all individual runs,

$$g = + 2.160 \pm .004$$

From Knight shift measurements on Rh in Rh-metal by Seitchik et al.¹²⁾ it is known that a correction of $\frac{\Delta H}{H} = 0.43\%$ has to be applied, which brings the final value to $g = + 2.151 \pm 0.004$. This g-factor could serve as a standard reference value in work with perturbed angular correlations, not only because of its accuracy but also because of the reproducibility of the source. No chemistry is involved and the source was simply a piece of the rhodium metal target on which a (p,4n) reaction was induced by 42.5 MeV protons to produce the ¹⁰⁰Pd activity.

The performance of this method, its simplicity and accuracy leaves no doubt that it will be most useful for future investigations of hyperfine interactions in isomeric states with half-lives between 10^{-8} and 10^{-3} sec. It should be noted that the measuring time for the runs listed in table II was about 24 hours. This, together with the fact that for a pure frequency determination one only needs to measure at one field direction and angle, underlines the practical advantage of the method in addition to the other features mentioned above. Further, if even the sign of the anisotropy is unknown, this and the sign of the g-factor can be unambiguously determined by a set of two measurements including one of the angles 90° or 180° , as can be seen from table I.

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Table I. Expected values for the phase, $\phi(\nu)$, of the Fourier transform for various detector geometries, θ_0 , and magnetic field directions. All angles are counted clockwise from the γ_1 -toward the γ_2 -direction. The magnetic field directions "up" and "down" refer to the detector plane.

Sign of g-factor	+		-	
Sign of A_2	+	-	+	-
135° up	$\pi/2$	$-\pi/2$	$-\pi/2$	$\pi/2$
135° down	$-\pi/2$	$\pi/2$	$\pi/2$	$-\pi/2$
225° up	$-\pi/2$	$\pi/2$	$\pi/2$	$-\pi/2$
225° down	$\pi/2$	$-\pi/2$	$-\pi/2$	$\pi/2$
90° up	π	0	π	0
90° down				
180° up	0	π	0	π
180° down				

Table II. Summary of g-factor measurements with a Rh-metal source. The angle θ_0 describing the geometry of the detectors is counted clockwise (cw) from γ_1 toward γ_0 . The arrow indicates the field direction with respect to the detector plane. The frequency values have been obtained from the derivative of the resonance peak.

run no.	θ_0 (degrees)	Magnetic Field (gauss)	Frequency (MHz)	g-factor	Phase ϕ
1	135	4996 ± 10 ↑	16.46 ± 5	$2.161 \pm .008$	$\pi/2$
2	180	4996 ± 10 ↓	16.52 ± 5	$2.169 \pm .008$	0
3	90	4996 ± 10 ↓	16.50 ± 5	$2.166 \pm .008$	$-\pi$
4	180	7636 ± 7	25.17 ± 5	$2.162 \pm .005$	0
5	180	7636 ± 7	25.04 ± 5	$2.151 \pm .005$	0
				Weighted average: $2.160 \pm .004$	

FIGURE CAPTIONS

Fig. 1. Frequency spectrum of the Fourier transform, $F(\nu)$, of the normalized data and of the Fourier transform, $G(\nu)$, of the autocorrelation function.

The spectrum shown represents run no. 1 in table II.

Fig. 2. Frequency spectrum of the sine, $A(\nu)$, and cosine, $B(\nu)$, transforms, and of the absolute function $F(\nu)$. The data represent run 4 of table II.

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Fig. 1

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Fig. 2

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