ANNALES
UNIVERSITATIS MARIAE CURIE-SKŁODOWSKA
LUBLIN — POLONIA

VOL. XLIII/XLIV, 9 SECTIO AAA 1988/1989

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Study of the Magnetic Hyperfine Interactions by Perturbed Angular Correlations Method

This work is devoted to Professor Mieczysław Subotowicz - coorganizer of studies carried out by a group of physicists from Lublin in the Joint Institute of Nuclear Research in Dubna, on the occasion of his 65th birthday and 45th anniversary of his scientific work.

Like other nuclear methods of solid state studies the method of Perturbed Angular Correlations (PAC) of γ radiation has some important advantages:

1. Detection of radiation signals from individual nuclei ensures extra high sensitivity. Measurements can be performed for so low concentrations of nuclear probes, that the probes themselves do not influence the properties of investigated host material.

2. Information comes from probes of very small dimensions sensitive to their local environment, which makes possible looking into the microscopic properties of the investigated materials.

3. Utilisation of penetrating nuclear radiation permits the investigation of samples placed inside chambers with notable wall thickness. This is especially important when measurements are performed at low or high temperatures or under high pressures.

The principle of the PAC method is based on the influence of the extranuclear electromagnetic fields on the angular distribution of γ - quanta emitted in the cascade going through the intermediate excited state characterized by a certain mean - life τ and certain values of its magnetic dipole and electric quadrupole moments (Fig.1). The emission of the second photon (γ_2) with regard to the direction of the first one (γ_1) is anisotropic in the majority of cases.

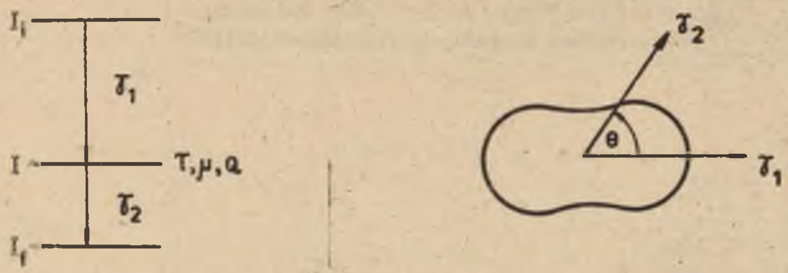
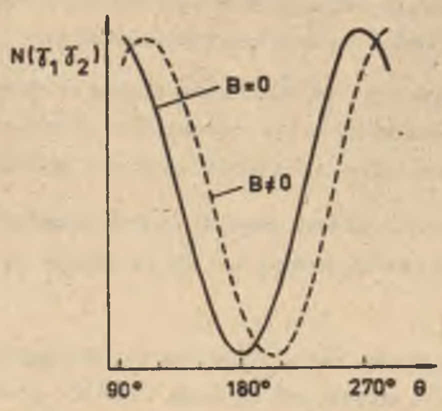


Fig. 1 a) A γ-ray cascade. *b) Angular distribution of γ-rays.*

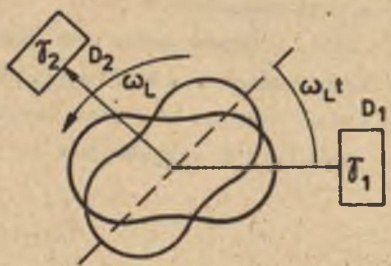
If during the lifetime of the intermediate excited state with a dipole magnetic moment μ, the magnetic field B acts on the nucleus, the nucleus precesses in this field, which gives rise to a change in the angular distribution of the emitted radiation.



If the mean - life of the excited state is so short or the friquency of the Larmor precission (ω_L) of the nuclear magnetic moment is so small, that the relation $\omega_1\tau << 1$ is fulfilled, the angular distribution of γ-radiation is shifted by a small angle $\Delta\Theta \approx \omega_1\tau$. This is the principle of the time - integral PAC method and it is schematically shown in Fig. 2.

If $\omega_1\tau >> 1$ and the resolving time (τ_0) of the spectrometer is shorter than the mean - life τ of the excited state, then the application of the time-differential method is possible. The time-differential perturbed angular correlation (TDPAC) method was proposed and applied for the first time by Deutsch and Hrynkiewicz [1, 2] in 1959. This method provided new possibilities for studying the hyperfine interactions. Some modifications of this method were realized only 25 years later [3].

In the case of the magnetic dipole interaction the time dependence of the coincidence rate of γ_1 and γ_2 photons is modulated by the Larmor precession. The idea of the TDPAC method is schematically shown in Fig. 3.



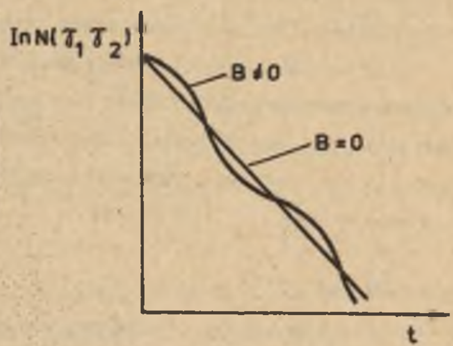


Fig. 3 a) Rotation of angular correlation pattern with Larmor frequency ω_L. *b) Time-differential angular correlation spectrum.*

Both variants of the PAC method (integral and differential) make possible the determination of the Larmor precession freqnency given by the formula

$$\omega_L \doteq \frac{\mu B}{I\hbar},$$

where μ and I are the magnetic moment and the spin of the intermediate state, respectively, and B is the magnetic field, which acts on the nucleus. Thus the knowledge of the exact value of B permits determination of the magnetic moment of the nucleus state, and vice versa, when knowing the value of the magnetic moment of the nuclear probe, one can determine the magnetic field acting on it.

The development of the PAC method in the Institute of Nuclear Physics in Cracow was possible due to the availability of radioactive samples from JINR Dubna obtained there on the proton beam of the synchrocyclotron in the Laboratory of Nuclear Problems (LNP). The examples of the application of the TDPAC method are measurements of the magnetic moments of the excited state 87 keV in ^{155}Gd [4] and of the two excited states 122 keV and 198 keV in ^{147}Sm [5]. The collaboration with JINR Dubna resulted in the formation of a group of Cracow physicists in the Laboratory of Nuclear Reactions (LNR), engaged in the studies in magnetic materials of hyperfine interactions of radioactive isotopes obtained in reactions with heavy ions.

Similar measurements, started in 1969, were performed by a group of physicists from Lublin headed by Professor W. Żuk. The short-lived isotopes obtained in the reaction of nuclear spallation in the beam of the Dubna synchrocyclotron were used as nuclear probes. Meanwhile the PAC measurements with long-lived isotopes obtained from Dubna were started in Lublin. Professor M. Subotowicz and his coworkers were performing measurements of the $\beta-\gamma$ correlation and of the longitudinal electron polarization related to the problem of the non - conservation of parity in weak interactions.

In the Laboratory of Nuclear Reactions in JINR the nuclear probes with known magnetic moments of excited states were used for the determination of internal magnetic fields in Fe, Co, and Ni hosts. The products of nuclear reactions were either directly created in the appropriate magnetic materials or implanted into magnetic foils due to their recoil energy.

Table 1. Ways of obtaining and characteristics of nuclear probes.

nuclear reaction	mother - nucleus and its mean-life	nuclear probe	cascade [keV]	mean - life of the intermediate state [ns]
^{59}Co(^{12}C, 4n)^{67}As$\rightarrow$ ^{67}Ge $\rightarrow$ ^{67}Ga	^{67}Ga(78h)	^{67}Zn	206 - 184	1. 0
^{56}Fe(^{12}C, 2n)^{66}Ge and ^{59}Co(^{11}B, 4n)^{66}Ge	^{66}Ge(2.3h)	^{66}Ga	190 - 44 and 66 - 44	18. 0
^{71}Ga(^{11}B, 5n)^{77}Kr $\rightarrow$ ^{77}Br	^{77}Br(57h)	^{77}Se	755 - 250 and 585 - 250	9. 3

The TDPAC method was successfully applied even in the case of ^{67}Zn nucleus, whose mean life time of the intermediate state of 184 keV is equal to 1 ns. It was quite an achivement at that time with NaI(Tl) scintillation detectors used. Fig. 4 shows the dependence of internal magnetic fields acting on nuclei of sp - type impurities (IV period) on the magnetic moments of Fe, Co, and Ni host atoms [6, 7].

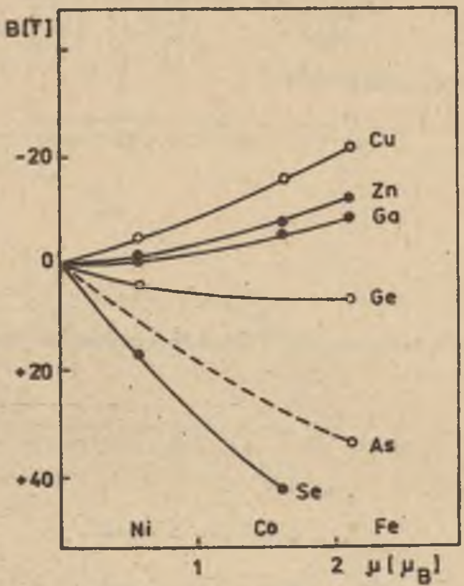


Fig. 4 Internal magnetic fields on nuclei of sp - type impurities in Fe, Co and Ni hosts. Black circles present the results of measurements performed by the Cracow group in LNR Dubna.

The group from Lublin was engaged in the measurements of magnetic moments of low-excited states in neutron-deficient nuclei from the rare earth element region. The example of the investigation carried out in the LNP are measurements with the ^{151}Gd and ^{153}Gd nuclear probes - Fig. 5 [8].

With time physicists from the Moscow University, from Uzbekistan and Romania joined the Polish group working in LNP. The metallic matrices (Fe, Co, Ni and Gd) have been replaced by their compound. The subject of special interest became the quasi-binary Laves phase compounds containing the rare earth elements. Some of them show high stability of the hyperfine interaction parameters. $(Zr_xHf_{1-x})Fe_2$ can serve as examples. The substitution of 60 per cent of Zr atoms with isoelectronic Hf has no influence on the value of the internal magnetic field measured on ^{181}Ta (daughter of ^{181}Hf) by means of

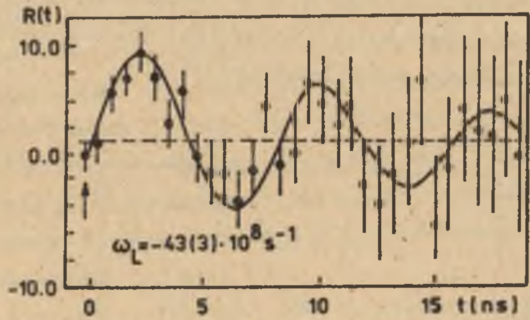


Fig. 5 Spin precession of 108 keV statest in ^{151}Gd in Fe host obtained by means of TDPAC method.

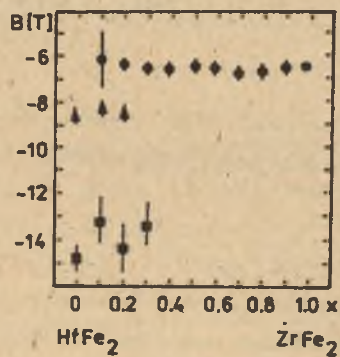


Fig. 6 Internal magnetic fields on ^{181}Ta nuclei in $(Zr_X Hf_{1-X})Fe_2$ Laves phase compounds as a function of x. An abrupt change of the hyperfine field from ≈ -14 T in $HfFe_2$ ( ) to ≈-6.5 T at x = 0.1 (•) is demonstrated. In the rang $0 < x \leq 0.3$ the coexistence of both hfs components and also a third one, B ≈ -8.5 T (△), was observed.

the TDPAC method - Fig. 6 [9]. Compounds containing lanthanides deserve special, interest because of their specific and surprising magnetic properties, which are due to an unfilled 4f electronic shell. A good example are measurements of the internal magnetic fields on ^{181}Ta in $GdFe_2$. It turns out that their values as well as their temperature dependences are notably different for samples synthesised under normal and high (7.7 GPa) pressures - Fig. 7 [10].

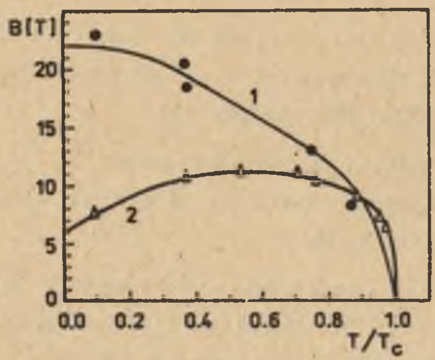


Fig. 7 Temperature dependence of internal magnetic fields on ^{181}Ta in $GdFe_2$ samples prepared [1] under normal pressure [2] under high pressure (7.7 GPa).

The X - ray patterns show identical lattice structures and the same lattice constant a=7.40 Å [18]. The authors suggest that the contributions from the magnetic sublattice of Gd in the samples prepared under normal and high pressures have the same absolute values, but their signs are opposite.

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