ABOUT THE PARAMETRIZATIONS OF THE TRANSIENT FIELD UTILIZED IN NUCLEAR MAGNETIC MOMENTS MEASUREMENTS

ACERCA DE LAS PARAMETRIZACIONES DE CAMPO TRANSIENTE USADAS EN LA MEDICIÓN DE MOMENTO MAGNÉTICO NUCLEAR

Ana M. Gómez[1], Diego A. Torres.[2]

[1] Programa de Física, Universidad del Quindío, Armenia, Colombia.
[2] Departamento de Física, Universidad Nacional de Colombia, Bogotá D.C., Colombia.

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Abstract

The intensity of the magnetic field produced by the spin-orbit interaction, which is the base for measurements of nuclear magnetic moments with short lifetimes excited states, is usually parametrized by functions that depend on the interacting ions and the stopping material. In this contribution, some of these parametrizations will be presented in order to discuss the role that they occupy in the measurement of nuclear magnetic moments of excited states of short duration.

Keywords: Nuclear magnetic moments, Transient Field, g factors, nuclear structure.

Resumen

La intensidad del campo magnético producido por la interacción espín orbita, el cual es la base de las medidas de momento magnético nuclear con estados excitados de muy corta duración, es usualmente parametrizado por funciones que dependen de la interacción de iones y un

[1] *amgomezl_1@uqvirtual.edu.co*
[2] *datorresg@unal.edu.co*

material de frenado. En ésta contribución, algunas de éstas parametrizaciones serán presentadas con el fin de discutir el papel que juegan en la medición de momento magnético nuclear de nucleos con estados excitados de corta duración.

Palabras clave: Momento magnético nuclear, Campo Transiente, Factor g, estructura nuclear.

Introduction

The measurements of nuclear magnetic moments is to date the best tool to identify and characterize the nucleon's currents which dominate the nuclear wave function. The systematic study of nuclear magnetic moments, in several mass regions, has been a decisive tool for the comparison of different nuclear structure models. The Transient magnetic Fields (TF), which appears in the interaction of ions moving at around the Bohr velocity inside a ferromagnetic polarised material, presents the high strength ($\sim$ 100T) [1] that makes possible the experimental study of nuclear magnetic moments of nuclei in excited states with short lifetimes ($\sim$ ps).

Different parametrizations of the TF are being used by groups performing experimental studies of nuclear g factors, and a description from first principles of the nature of the TF is one of the challenges that should be addressed during the forthcoming years [2].

In this contribution a short review of the most common parameterizations utilized in nuclear magnetic moments measurements, in short-lived excited states, will be presented. A special emphasis will be made in their range of use and the challenges that future parameterizations should address.

Nuclear Magnetic Moments Measurements

The precession angle, $\Delta\theta$, of the nuclear spin originated by the interaction between the nuclear magnetic moment and the TF is given by

$$\Delta\theta = -\frac{g\mu_N}{\hbar}\int_{t_{in}}^{t_{out}} B_{TF}(v(t), Z)e^{-\frac{t}{\tau}}dt. \tag{1}$$

In Eq. (1) the information about the magnetic moment is located in the so called g factor, $g = \frac{\mu/\mu_N}{I/\hbar}$, where μ_N is the nuclear magneton and I is the nuclear spin of the state; B_{TF} denotes the transient field as a function of the velocity v of the ion inside a ferromagnetic and the atomic number Z of the nucleus, τ is the lifetime of the considered state and t_{in} (t_{out}) are the input (output) times of the nucleus into the ferromagnetic material. The exponential factor of decay ($e^{-\frac{t}{\tau}}$) is the relationship between the amount of time in which the nucleus is embedded in the ferromagnetic material and the lifetime. The term B_{TF} denotes the intensity of the *TF*. A function for B_{TF} obtained from first principles is difficult to obtain due to the complexity of the microscopic description of the spin-orbit interaction. Some of those difficulties are addressed with a certain level of details in Refs. [1, 3].

The lack of a microscopic detailed description of B_{TF} has been overcome by applying a parametric representation for the field strength based on calibration measurements. Below we will describe the most utilized B_{TF} parametrization in the measurements of nuclear magnetic moments with the *TF* technique.

Transient field parametrizations

The transient field parametrizations represent the field strength. They are used to calculate the field strength of the transient field for the given experimental condition, like velocity and charge of a probe ion.

All parametrizations depend on the protons number in the accelerated ion (Z), the velocity of the ion in the material relative to the Bohr's velocity (v/v_0) and a strength parameter a.

Rutgers Parametrization

$$B_{TF} = a \cdot Z^{1.1\pm0.2} \cdot \left(\frac{v}{v_0}\right)^{0.45\pm0.18} \cdot M \tag{2}$$

This is the only one parametrization that includes the magnetization of the ferromagnetic material (M) and a non-linear dependence for Z and (v/v_0). The strength parameter has a value of $a = 96.7 \pm 1.6$. Table 1 presents the g-factor values utilized for the fit of the parametrization, only one isotope has been used in a Gd layer. The magnetization for this case is proportional to the number of electrons per atom polarized and it has to be known for each ferromagnetic layer. The parametrization is valid for a broad range of isotopes ($8 < Z < 80$).

Iron					Gadolinium				
Nucleus	$g(2_1^+)$	τ (ps)	Technique	Ref.	Nucleus	g	τ (ps)	Technique	Ref.
^{20}Ne	0.54(4)	1.0	RIV/D	[4]					
^{24}Mg	0.51(2)	2.0	IMPAC	[5]					
^{28}Si	0.53(2)	0.68	IMPAC	[6]					
^{56}Fe	0.60(8)	10	IPAC, R	[7]					
^{82}Se	0.42	16.3	IMPAC	[8]	^{82}Se	0.42	16.3	IMPAC	[8]
^{106}Pd	0.40(2)	16.9(9)	IPAC, R	[9]					
^{110}Cd	0.28(5)	7.7(6)	IPAC	[10]					
^{134}Ba	0.43(5)	7.0	IMPAC	[11]					
^{148}Nd	0.33(4)	123(3)	IMPAC	[12]					
^{194}Pt	0.274(25)	60(4)	IPAC	[13]					

TABLE 1. g-factor measurements and lifetimes for nuclei traversing in iron (right) and gadolinium (left) used for the formulation of the Rutgers parametrization. The convention for the information about the experimental techniques follows the convention of [14].

Bonn Parametrization

$$B_{TF} = a \cdot Z \cdot \left(\frac{v}{v_0}\right)^p \cdot G \cdot R(Z) \tag{3}$$

where $R(Z)$ is the relativistic correction which is ≈ 1 for values of $Z \gtrsim 30$. The a and p parameters are 12.3 ± 1.7 T [1] and 1.06 ± 0.25 respectively [16], to obtain a linear dependence in (3) the p parameter was taken as ≈ 1. The TF was estimate from the adjusted Lindhard and Winther theory [1-4] (ALW) [16]. The G parameter differ for each ferromagnetic layer of Gadolinium and Iron and is given by: $G = 1 - \alpha\frac{1-e^{\lambda_\Gamma t_{eff}}}{\lambda_\Gamma t_{eff}}$, where the probability of loss of ferromagnetism α is 1.0(1) and 0.5(1) and the decay constant λ_Γ^{-1} is 0.4(1) ps and $\gtrsim 1.0$ ps for Fe and Gd respectively [17]. The nuclei arranged in Table 2 which are excited via proton inelastic

[1] Valid for average number of polarized electrons per Fe [15].

scattering. Bonn parametrization is *valid for larger atomic numbers* ($Z \gtrsim 10$) [16].

Iron				
Nucleus	g-factor	τ (ps)	Technique	Ref.
^{16}N	$g(1^-)$=-1.83(1)	4.5	RIV/D	[18]
^{18}O	$g(2_1^+)$=-0.19(3)	2.07	RIV/D	[19]
^{22}Ne	$g(2_1^+)$=0.325(2)	3.6	RIV/D	[20]
^{24}Mg	$g(2_1^+)$=0.51(4)	1.45	IMPAC	[21]
^{56}Fe	$g(2_1^+)$=0.61(16)	6.9	IMPAC	[22]
^{196}Pt	$g(2_1^+)$=0.345(3)	34	IPAC	[23]

TABLE 2. g-factor measurements, used in the construction of the Bonn parametrization, obtained from different experimental techniques [14].

Chalk River Parametrization

$$B_{TF} = a \cdot Z \cdot \left(\frac{v}{v_0}\right) \cdot e^{-\beta \frac{v}{v_0}} \tag{4}$$

The Chalk River and Rutgers parametrizations are contemporary. In the experiment it was found a fudge factor to account for the observed down turn of the B_{TF} for larger Z. The B_{TF} has linear dependence with Z and v/v_0. This parametrization take into account the decline of TF in the region of high velocities and this is *valid in a regime of velocities of* $6v_0 < v < 10v_0$ *for iron and* $2.4v_0 < v < 10.2v_0$ *for gadolinium, is specially calibrated for the region of heavy nuclei and rare earth.* The g factors used in the calibration of the TF are arranged in Table 3, which were excited via Coulomb excitation being impacted by radioactive beams. For ions traversing into layers of iron the strength parameter is $a = 15.5 \pm 0.8$ T and $\beta = 0.1$. The values of a and β for Gd layer are arranged in Table 3.

Stuchbery Parametrization

$$B_{TF} = a \cdot Z^P \cdot \left(\frac{v}{Zv_0}\right)^2 \cdot e^{\left(\frac{v}{2Zv_0}\right)^4} \tag{5}$$

Stuchbery's idea was to have a parametrization for high velocity projectiles were the probe ions are mostly bare. This

Iron					Gadolinium				
Nucleus	g-factor	τ (ps)	Technique	Ref.	Nucleus	$g(5/2^-)$	τ (ps)	Technique	Ref.
^{169}Tm	$g(1/2^+)$=0.1145	stable	AB/D	[24]					
^{152}Sm	$g(4^+)$= 0.42(3)	56.6	IMPAC	[25]	^{207}Pb*	0.303(1)	186	IPAC	[26]
^{154}Sm	$g(4^+)$=0.392(2)	165	IMPAC	[25]					
^{158}Gd	$g(4^+)$=0.362(1)	148	IPAC	[25]		$\langle I\rangle(\hbar)$	a (T)	β	Ref.
^{156}Gd	$g(4^+)$=0.387(1)	112	IPAC	[25]					
^{174}Yb	$g(4^+)$=0.338(1)	144	CER	[25]	^{232}Th**	7.9	26.9(16)	0.1	[26]
^{156}Dy	$\overline{g}(4^+)$=0.44(5)	73	IPAC	[27]	^{238}U**	8.8	31.2(17)	0.1	[26]

TABLE 3. g-factor measurements for nuclei in Fe (right) and Gd (left); used in this calibration, with the respective experimental techniques [14]. The nucleus of ^{232}Th and ^{238}U (left), were taken into account experimental measurements of precession in different energy transitions to the calibration of TF; for which presents the average value of the spin on the table. * For these nucleus was assumed a factor $g = Z/A$. ** To lead the force parameter $a = 28.0 \pm 2.6$ and $\beta = 0.13 \pm 0.03$ [26].

parametrization has a non-linear dependence with Z and v/v_0. The constants a and P are 1.82 ± 0.05 T and 3 for Fe and 26.7 ± 0.1 T, 2 to Gd respectively. Stuchbery formulation can be applied to the general concept of distribution of charge state 1s. This parametrization *is valid for ions at high velocities* ($v_L \equiv \frac{1}{2Zv_0}$) *and a range of atomic number* $6 < Z < 16$ *(light ions)* . For the experimental measurement of g factor the nuclei arranged in Table 4 were used, this measures were made by the Rutgers group [28].

Iron					Gadolinium				
Nucleus	g-factor	$\tau(ps)$	Technique	Ref.	Nucleus	Φ(mrad)	t_{eff} (fs)	state	Ref
$^{13}_{6}$C	$g(5/2^+) = -0.59(5)$	11.8(6)	RIV/D	[29]	$^{16}_{8}$O	3.6(3)	361(35)	3^-	[30]
$^{16}_{8}$O	$g(3^-) = 0.55(3)$	26.6(7)	IMPAC	[31]	$^{20}_{10}$Ne	2.74(40)	190(19)	2^+	[32]
$^{20}_{10}$Ne	$g(2^+) = 0.54(4)$	1.04(9)	CER	[33]	$^{28}_{14}$Si	5(10)	140(8)	2^+	[34]
$^{24}_{6}$Mg	$g(2^+_1) = 0.51(2)$	1.57(5)	CER	[33]		7.0 (14)	207(8)	2^+	[35]
$^{28}_{14}$Si	$g(2^+) = 0.59(9)$	0.49	CER	[36]	$^{32}_{16}$S	g-factor	τ(ps)	Technique	Ref.
$^{32}_{16}$S	$g(2^+) = 0.47(9)$	0.16	CER	[37]		0.50(3)	0.246(9)	CER	[35]

TABLE 4. g-factor and precession angle measurements used in the Stuchbery parametrization. The experimental techniques of g were taken of Ref. [14].

Discussion

In this contribution a short overview of the parametrizations utilized in the TF technique has been presented. All parametrizations depend on the speed of the ion and the Z of the target, either Gd or Fe. To date, no other materials have been utilized in experiments using the TF technique. The use of new designed materials that can be fabricated controlling characteristics, such as the magnetization, should be explore.

In general all parametrizations presented in this contribution have comparable results in the particular range $2.0 < v/v_0 < 8.0$, and has obtained from a g factor in a specific velocity range [1]. A systematic comparison of the results of g factors using the four parametrizations could help to discriminate the differences between themselves, this is a work in progress that will be presented in a forthcoming paper.

All parameterizations are constructed for a region of truncated masses, none is universal, and the lack of theoretical developments in the area suggest that these parametrizations are going to be utilized for a while. Theoretical research in this topic should be encourage to be incentive.

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