AIP Conference Proceedings

RESEARCH ARTICLE | JANUARY 15 2019

Resonant magnetic Bragg polarimeter

H. Adachi

Check for updates

AIP Conf. Proc. 2054, 060048 (2019)
https://doi.org/10.1063/1.5084679

View Online
Export Citation
CrossMark

Articles You May Be Interested In

X-ray polarimeter with a transmission multilayer

Rev. Sci. Instrum. (February 2010)

A Graphite Crystal Polarimeter for Stellar X-Ray Astronomy

Rev Sci Instrum (November 2003)

Tensor polarimeters

AIP Conference Proceedings (May 1989)

28 September 2023 15:34:59

500 kHz or 8.5 GHz?
And all the ranges in between.
Lock-in Amplifiers for your periodic signal measurements

Find out more
Zurich Instruments

AIP Publishing

Resonant Magnetic Bragg Polarimeter

H. Adachi[1, a)]

[1]*Institute of Humanities, Shinshu University, Matsumoto 390-8621, Japan*

[a)]Corresponding author: adachih@shinshu-u.ac.jp

Abstract. The theoretical formulae for the relative change in the x-ray scattering intensity from a ferromagnetic material upon the magnetization reversal are derived for three particular cases of the magnetization direction with the model where the magnetization dependence arises from the resonant magnetic scattering of electric dipole transitions under no crystal field. With illustrating the numerical results, the prospects for the application of the resonant magnetic scattering to the x-ray polarimetry are discussed.

INTRODUCTION

The first explicit mention of the application of the magnetic x-ray scattering to polarimetry dates back to the early 1950s, which was made in the context of the nuclear physics [1]. Since then, the intensity variation of an order of 1% of the Compton scattering from the Fe metal upon the magnetization reversal has been utilized as the only practical mechanism for sensing the circular polarization of x rays [2]. Though the magnetic x-ray scattering is also sensitive to the linear polarization, some simpler methods making use of, for example, the 90-degree scattering by a non-magnetic target material are well known and ordinarily adopted as the linear polarimeters.

Recently, in the course of the data analysis of the magnetic x-ray diffraction experiment on the ferromagnetic intermetallic compound of $GdAl_2$, we have theoretically found that the dependence of the x-ray scattering on the target magnetization can be dramatically magnified [3]. The point of the idea, which is not restrictive to $GdAl_2$ but widely applicable to the ferromagnetic crystalline systems comprising plural atomic species, is to aim at the pseudo-extinction of an ordinary electric diffraction signal in the vicinity of an x-ray absorption edge. This method is independent of the other enhancement factors hitherto known [4-7] and is capable of making the magnetization dependence still clearer by itself or combining together with them.

In this paper, the theoretical formulae for the relative change in the x-ray scattering intensity from a ferromagnetic material upon the magnetization reversal for three particular cases of the magnetization direction are reported, which have been derived with the model where the magnetization dependence arises from the resonant magnetic scattering of electric dipole transitions under no crystal field. This model is known as a good approximation for the magnetic scattering at, for example, the rare-earth $L_{\mathrm{II,\,III}}$ resonances [3-6]. With illustrating the numerical results, the prospects for the application of the resonant magnetic scattering to the x-ray polarimetry are briefly discussed.

RELATIVE INTENSITY CHANGE UPON MAGNETIZATION REVERSAL

The starting point of the calculation is the following scattering amplitude [3, 8, 9]:

$$F_e\begin{pmatrix}1 & 0\\ 0 & \cos 2\theta\end{pmatrix}+F_m\begin{pmatrix}0 & z_1\cos\theta+z_3\sin\theta\\ -z_1\cos\theta+z_3\sin\theta & -z_2\sin 2\theta\end{pmatrix} \tag{1}$$

Proceedings of the 13th International Conference on Synchrotron Radiation Instrumentation – SRI2018
AIP Conf. Proc. 2054, 060048-1–060048-4; https://doi.org/10.1063/1.5084679
Published by AIP Publishing. 978-0-7354-1782-3/$30.00

28 September 2023 15:34:59

where two photon states with the linear polarization perpendicular and parallel to the scattering plane are taken as a basis set in a 2×2 matrix form, F_e is the electric scattering amplitude including conventional dispersion effects, F_m is the amplitude of the resonant magnetic scattering, θ is the Bragg angle, and the vector **z** is the magnetization direction of a target material whose components, namely directional cosines, refer to the $u_1u_2u_3$ frame depicted in the inset of Fig. 1(a). Note that the notation of F_m is adopted here instead of $i\ A_{(1)}$ used in Ref. [3] for intuitive understandability. With this model, the relative change in scattering intensity upon the magnetization reversal is calculated as follows:

$$R = \frac{\left[\left(F_e'F_m' + F_e''F_m''\right)\cdot P_L \sin 2\alpha \sin^2\theta - \left(F_e'F_m'' - F_e''F_m'\right)\cdot P_C \cos^2\theta\right] 4\cos\theta}{|F_e|^2\left[(1-P_L\cos 2\alpha)+(1+P_L\cos 2\alpha)\cos^2 2\theta\right]+|F_m|^2 2\cos^2\theta} \tag{2}$$

$$R = \frac{-\left(F_e'F_m' + F_e''F_m''\right)\cdot(1+P_L\cos 2\alpha)2\cos 2\theta \sin 2\theta}{|F_e|^2\left[(1-P_L\cos 2\alpha)+(1+P_L\cos 2\alpha)\cos^2 2\theta\right]+|F_m|^2(1+P_L\cos 2\alpha)\sin^2 2\theta} \tag{3}$$

$$R = \frac{\left[\left(F_e'F_m' + F_e''F_m''\right)\cdot P_L \sin 2\alpha \cos^2\theta - \left(F_e'F_m'' - F_e''F_m'\right)\cdot P_C \sin^2\theta\right] 4\sin\theta}{|F_e|^2\left[(1-P_L\cos 2\alpha)+(1+P_L\cos 2\alpha)\cos^2 2\theta\right]+|F_m|^2 2\sin^2\theta} \tag{4}$$

where Eqs. (2), (3), (4) are the formulae for the cases when the target magnetizations are flipped along the u_1, u_2, u_3 axes respectively, single and double primes attached to F_e and F_m indicate the real and imaginary parts, P_L and P_C are the degree of linear polarization and that of circular one of the incoming x rays, and α is the angle formed by the electric vector of the linear-polarization component with the scattering plane (the u_1u_3 plane). The calculation of the scattering cross section with the polarization density matrix is detailed in, for example, Ref. [10]. Two Stokes parameters corresponding to linear polarizations at an angle of 45 degrees should be expressed with P_L and α at the final stage of calculation.

As an example, R of Eq. (2) is graphed for some parameters in Fig. 1. Keeping in mind our recent finding mentioned in the introduction, the results for the cases where the size of F_e is relatively close to that of F_m are shown here. Note that, in our previous experimental work, the magnetic asymmetry corresponding to R can be well identified down to an order of 10^{-3} (0.1%) [3].

The present results show that, for example, when the target magnetization is flipped within the scattering plane, the states of the linear and circular polarizations of an incoming x-ray beam are known through the two-fold modulation and the asymmetry with respect to the zero line in the R versus α behavior, respectively. When θ approaches to 0, the right hand sides of Eqs. (3) and (4) become 0 because of the geometrical factors and Eq. (2) is reduced to the following expression:

$$R = -2P_C \frac{F_e'F_m'' - F_e''F_m'}{|F_e|^2 + |F_m|^2}. \tag{5}$$

This means that, in the forward-scattering geometry, R is independent of P_L and proportional to P_C. The same expression is also obtained from Eq. (4) with $\theta \to \pi/2$, namely, in the back-scattering geometry. Although no more than approximate estimates, the expressions and the numerical results thus obtained will serve as guidelines for designing and/or interpreting the measurements of R for, for example, the rare-earth $L_{\mathrm{II,\ III}}$ resonances, and the polarization state of an incoming beam will be, if unknown, estimated through such measurements of R with, in practice, the aid of the reference data separately measured with the synchrotron radiations having known parameters.

PROSPECTS FOR THE APPLICATION TO POLARIMETRY

In general, the method of drawing information on the x-ray polarization from R has some attractive features. First, by nature, R is a relatively robust quantity against spurious effects because background noise and/or systematic errors can be partly eliminated through the process of subtracting, adding, and ratioing between plural intensity data.

28 September 2023 15:34:59

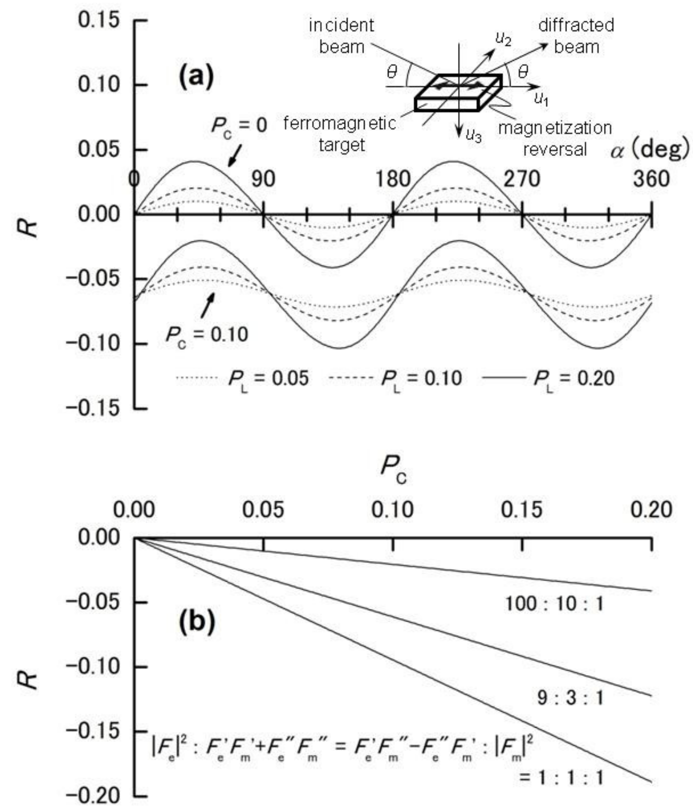

FIGURE 1. Numerical results of the relative change in x-ray scattering intensity upon the polarity reversal of the target magnetization. The magnetization is supposed to be flipped along the u_1 axis shown in the inset and the scattering angle 2θ is set to be 60 degrees. (a) The dependence on the azimuthal angle around the incoming beam axis α. As to the ratio of the magnitudes of the electric and magnetic scattering amplitudes, $|F_e|^2 : F_e'F_m'+F_e''F_m'' = F_e'F_m''-F_e''F_m' : |F_m|^2$ is assumed to be 9 : 3 : 1. The inset shows the scattering layout and some definitions. (b) The dependence on P_C. The degree of linear polarization P_L is set to be 0, the results are independent of α.

Second, as described above, the parameters not only for linear polarization but also for circular one can be estimated. Third, as the data are taken with periodically flipping the target magnetization, the measurements synchronized or, on the contrary, being out of phase with the other periodic phenomenon can be programmed. Such phase sensitive measurements may be also useful to further improve the signal-to-noise ratio. If R becomes one or two orders of percentage higher, the polarimeter of the magnetic scattering type having these features may open up a new vista of some experiment at the synchrotron or FEL facility or with the laboratory x-ray source.

Another interesting idea is the possible application to the astronomical observations. Since the first detection of the x rays from sources outside the solar system in 1962 [11, 12] opened the door to the so-called x-ray astronomy, various exotic heavenly bodies accompanied by the x-ray emission, including black holes, quasars, neutron stars, have been revealed and been fascinating not only scientists but also general people. X rays are undoubtedly the most crucial and direct probes for these astrophysical phenomena and observationally the spatial and/or temporal intensity profiles and the energy spectra have been investigated. The polarization properties are also believed to carry key information about the x-ray emission mechanism or the structure but have hardly been analyzed because the detection technique for an inconspicuous polarization in a limited flux of x rays is extremely delicate. While the reports on the interesting high-energy astrophysical phenomena, such as active galactic nuclei, gamma-ray bursts, magnetars, etc., have been increasingly accumulated and the fruitfulness of the polarization analysis for the x rays therefrom has become well recognized, the measurements hitherto tried have merely given the upper limits for the linear polarization for more than forty years since the pioneering work was done in the early 1970s [13], except for a few brightest x-ray sources [14-16]. Whereas the circular polarizations have been observed for longer wavelength region [17, 18], there exists no promising circular polarimeter for cosmic x rays up to now. The magnetic scattering

28 September 2023 15:34:59

polarimeter, capable of seeing circular polarization or of analyzing pulsating x-ray sources such as neutron stars, may contribute toward unraveling a mystery of the Universe.

There is no telling at the present stage whether the polarimeter making use of the resonant magnetic scattering will be practical or not. Narrowness of the energy band and weakness of the scattering power may become drawbacks. But an examination of the feasibility seems an interesting subject in future.

REFERENCES

1. O. Halpern, Nature **168**, 782 (1951).
2. H. Kawata, H. Adachi, and I. Matsumoto, AIP Conf. Proc. **705**, 549-552 (2004).
3. H. Adachi, H. Kawata, and M. Ito, J. Appl. Cryst. **48**, 1114-1121 (2015).
4. M. Blume, J. Appl. Phys. **57**, 3615-3618 (1985).
5. J. P. Hannon, G. T. Trammell, M. Blume, and D. Gibbs, Phys. Rev. Lett. **61**, 1245-1248 (1988); Phys. Rev. Lett. **62**, 2644(E) (1989).
6. P. Carra, M. Altarelli, and F. de Bergevin, Phys. Rev. B **40**, 7324-7327 (1989).
7. D. Hupfeld, O. Seeck, J. Voigt, J. Bos, K. Fischer, and Th. Brückel, Europhys. Lett. **59**, 284-290 (2002).
8. D. B. Pengra, N. B. Thoft, M. Wulff, R. Feidenhans'l, and J. Bohr, J. Phys.: Condens. Matter **6**, 2409-2422 (1994).
9. J. P. Hill and D. F. McMorrow, Acta Crystallogr. A **52**, 236-244 (1996).
10. S. Lovesey, J. Phys. C: Solid State Phys. **20**, 5625-5639 (1987).
11. Riccardo Giacconi, Hervert Gursky, Frank R. Paolini, and Bruno B. Rossi, Phys. Rev. Lett. **9**, 439-443 (1962).
12. Herbert Gursky, Riccardo Giacconi, Frank R. Paolini, and Bruno B. Rossi, Phys. Rev. Lett. **11**, 530-535 (1963).
13. R. Novick, M. C. Weisskopf, R. Berthelsdorf, R. Linke, and R. S. Wolff, Astrophys. J. **174**, L1-L8 (1972).
14. M. C. Weisskopf, E. H. Silver, H. L. Kestenbaum, K. S. Long, and R. Novick, Astrophys. J. **220**, L117-L121 (1978).
15. Knox S. Long, Gary A. Chanan, and R. Novick, Astrophys. J. **238**, 710-716 (1980).
16. P. Laurent, J. Rodriguez, J. Wilms, M. Cadolle Bel, K. Pottschmidt, and V. Grinberg, Science **332**, 438-439 (2011).
17. Jeremy Bailey, Antonio Chrysostomou, J. H. Hough, T. M. Gledhill, Alan McCall, Stuart Clark, François Ménard, and Motohide Tamura, Science **281**, 672-674 (1998).
18. K. Wiersema, *et al*., Nature **509**, 201-204 (2014).

28 September 2023 15:34:59