Hard X-ray Magnetic Circular Dichroism: application to spintronics materials

A. Rogalev

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Nobel Prize in Physics 1994: B. N. Brockhouse and C. G. Shull

Press release by the Royal Swedish Academy of Sciences:
“Neutrons are small magnets…… (that) can be used to study the relative orientations of the small atomic magnets. ….. the X-ray method has been powerless and in this field of application neutron diffraction has since assumed an entirely dominant position. It is hard to imagine modern research into magnetism without this aid.”
X-rays and magnetism

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Today:
X-ray magnetic circular dichroism (XMCD) is considered to be one of the most important discoveries in the field of magnetism research in the last two decades. It is hard to imagine modern research into magnetism without the aid of X-ray spectroscopy.
Outline

- Introduction to X-ray Magnetic Circular Dichroism
- Experimental aspects
- Selected examples
  - Magnetism in diluted magnetic semiconductors
  - Induced magnetism in magnetic multilayers
  - X-ray detection of magnetic resonance
- Conclusions
In 1895 Dr. W.K. Röntgen has discovered “Eine Neue Art von Strahlen”

On December 28, 1895 W.C. Röntgen had submitted his manuscript “On a New Kind of Ray, A Preliminary Communication” to the Würzburg Physical Medical Society.

On the 1st of January 1896 he sent copies of his manuscript to several renowned physicists.
Physique. — Quelques propriétés des rayons de Röntgen. Note de M. Jean Perrin, présentée par M. Mascart.

» Le bois, le papier, la cire, la paraffine, l’eau se montrèrent très transparents, l’influence de l’épaisseur restant cependant nette. Vendraient ensuite, à peu près rangés par ordre d’opacité croissante, le charbon, l’os, l’ivoire, le saphir, le verre, le quartz (parallèle ou perpendiculaire à l’axe), le sel gemme, le soufre, le fer, l’acier, le cuivre, le laiton, le mercure, le plomb. Ces résultats sont encore peu nombreux, et je ne peux songer à les relier par une loi générale; toutefois, on peut remarquer, dès maintenant, que les métaux sont en général moins transparents que les autres corps, mais n’ont pas l’opacité absolue qu’ils présentent pour la lumière. Si, par exemple, on superpose trois lames de fer, d’environ οmm, ο chacune, l’opacité ne paraît atteinte que dans la région commune aux trois lames.
"I may remark that I have made a large number of experiments on the opacity to these rays of plates of tourmaline (1) with their axes crossed, (2) with their axes parallel, testing the intensity of the rays which came through in some cases by their action on a photographic plate in others by the discharge they produced in an electrified plate on which they were incident. The result of these experiments were entirely negative, for although the tourmaline produced very considerable absorption of the rays, no difference was detected between the absorption when the axes were crossed and when they were parallel. It is very desirable that a large number of substances should be tested in this way."

J.J. Thomson
En poursuivant, avec de nouveaux tubes de Crookes, de formes diverses, les recherches que nous avons déjà soumises à l'Académie, nous avons obtenu de nouvelles photographies d'après lesquelles les centres d'émission des rayons X sont nettement caractérisés.

(" Travail fait au Laboratoire de Physique de l'École Normale.

(" Pour renforcer ces épreuves, nous avons eu recours à M. Bourinski, qui a récemment indiqué une méthode ingénieuse pour renforcer les négatifs faibles, méthode basée sur le principe de la superposition des pellicules (voir Bulletin de l'Académie impériale des Sciences de Saint-Pétersbourg, n° 4 avril 1895). La différence des teintes a été mise ainsi hors de doute, comme on peut le voir sur les épreuves que nous avons l'honneur de soumettre à l'Académie.

Il se présente une autre question. Les rayons X correspondant-ils à des vibrations longitudinales ou à des vibrations transversales? Cette question pourrait être tranchée si l'on pouvait démontrer qu'ils se polarisent. Les premières recherches que nous avons entreprises à ce sujet ont échoué. Nous avons alors fait préparer trois petites plaques de bournamine très minces (épaisseur de 0,001 mm). Sur la plus grande se posent les deux autres, une parallèlement et l'autre perpendiculairement à la première. S'il y a polarisation là où les plaques sont croisées, on doit s'attendre à voir l'action des rayons X affaiblie. Il va sans dire que l'action de la lumière ordinaire a été exclue et qu'on a changé plusieurs fois la position relative de ces plaques, afin d'éliminer toute influence d'égale épaisseur ou de manque d'homogénéité. Dans les huit épreuves obtenues, on peut distinguer que là où les plaques ont été croisées l'action photographique des rayons X a été moindre. On peut en conclure que les rayons X se polarisent et, par suite, qu'ils correspondent à des vibrations transversales.

(" D'après l'ensemble de nos recherches, l'existence, dans quelques cas, d'un centre d'émission d'origine anodique semble être mise désormais hors de doute. On observe en outre quelquefois que, si l'on interrompt à l'onde et le cathode, le nouveau centre anodique se produit là où se trouvait auparavant le centre cathodique, mais ce dernier est toujours plus intense.

Pour expliquer l'ensemble des faits observés, nous avons, dans notre Note précédente, proposé l'hypothèse des foyers, qui semble bien correspondre à tous les détails de nos expériences et qui, d'ailleurs, est d'accord avec ce fait, que les centres d'émission se trouvent d'ordinaire dans le voisinage de l'endroit où le verre du tube de Crookes devient fortement fluorescent, va que c'est précisément là que l'action des rayons cathodiques se concrétise. C'est cette hypothèse qui nous paraît offrir le plus de vraisemblance.

X-rays and Magnetism

search for polarised X-rays

Comptes rendus hebdomadaires des séances de l'Académie des sciences

Séance du lundi 23 Mars 1896

X-rays and Magnetism

search for dichroism with X-rays

Comptes rendus hebdomadaires des séances de l'Académie des sciences
Séance du lundi 30 Mars 1896
X-rays were everywhere and for everybody

How-to book gave step-by-step instructions on making radiographs, and included forms for ordering the equipment described.
X-rays and Magnetism

X-rays are polarised


XIII. Polarised Röntgen Radiation.

By CHARLES G. BARKLA, D.Sc. (Liverpool), M.Sc. (Vic.), B.A. (Cantab.), King's College, Cambridge; Otter Lodge Fellow, University of Liverpool.

Communicated by Professor J. J. THOMSON, F.R.S.

Received January 21,—Read February 16, 1905.

Though many attempts have been made to produce a beam of polarised X-radiation and to detect the polarisation by such methods as are applicable to ordinary light, the experiments have proved unsuccessful, and no evidence of polarity has been obtained. An arrangement of molecules such as occurs in crystals does not appear to affect a beam of this radiation transmitted through the crystalline substance.

The experiments here described were suggested by the results of an investigation of secondary radiation proceeding from gases and certain solids subject to X-rays, for it was found that the gases experimented upon were the source of a radiation differing little in character from the primary radiation which produced it. In some respects the difference was inappreciable, as, for instance, in the absorbability of the radiations by aluminium. The primary and secondary radiations differed slightly, however, in their ionising powers in air.† The energy of this secondary radiation was found to be proportional to the mass of gas through which the primary beam of definite intensity passed, and to be independent of the nature of the gas.

This led to the conclusion that this radiation is due to what might be called a scattering of the primary X-rays by the electrons constituting the molecules of the gas.

More recent experiments have shown that from light solids which emit a secondary radiation differing little from the primary, the energy of this radiation obeys the same law.

The phenomenon of secondary radiation from metals, however, is apparently much more complex, for in addition to secondary X-rays differing enormously in character from the primary, the metal radiator emits negative corpuscles. The total energy of these secondary radiations and the energy of the secondary X-rays alone are subjects

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Polariisation in Secondary Röntgen Radiation.

By CHARLES G. BARKLA, D.Sc. (Liverpool), M.Sc. (Victoria), B.A. (King's College, Cambridge), Demonstrator and Assistant Lecturer, University of Liverpool.

(Communicated by Professor J. J. THOMSON, F.R.S. Received January 17,—Read February 8, 1906.)

In a paper on "Polarised Röntgen Radiation," the writer gave an account of experiments which demonstrated the partial polarisation of a beam of X-rays proceeding from the antikathode of an X-ray focus-tube, and verified the theory previously given of the production of secondary X-rays in light substances.†

In that paper it was shown that the secondary radiation proceeding in a direction perpendicular to that of propagation of the primary radiation from certain substances placed in that primary beam should, according to the theory put forward, be plane polarised. From gases, however, the secondary radiation was not sufficiently intense to produce a tertiary of measurable intensity, and thus the polarisation of the secondary from them was not verifiable. On the other hand, though heavy metals were found to emit secondary radiation of sufficient intensity and ionising power to produce appreciable tertiary effects, in these metals the production of secondary radiation is a more complex phenomenon, and evidence of polarisation of the secondary beam is not to be expected from experiments upon them.

For the secondary radiator a substance had to be chosen which emitted a radiation of considerable intensity, yet differing very little in character from the primary. It had been shown that from such substances the intensity of radiation is proportional merely to the quantity of matter passed through by the primary of given intensity. A substance permitting the passage of the

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† J. J. Thomsen, 'Conduction of Electricity through Gases,' p. 392; C. G. Barkla, 'Phil.Mag.', June, 1903, and May, 1904.

† More precisely, substances of low atomic weight.
X-rays and Magnetism

X-rays are polarised

Shortly after I arrived at the conclusion as to the origin of secondary radiation from gases, Professor Wilberforce suggested to me the idea of producing a plane-polarised beam by means of a secondary radiator and of testing the polarisation by a tertiary radiator. The secondary radiation from gases under ordinary conditions is,

Plan of apparatus, showing position of bulb giving maximum deflection of electroscope $A_1$ and minimum of electroscope $A_2$.

Experimental set-up of Prof. Charles G. Barkla
X-RAY ABSORPTION SPECTROSCOPY AND MAGNETISM

X-rays and Magnetism


Introduction.

All the experimental evidence obtained within the last few years indicates the fundamental identity of X-rays and light: this evidence includes experiments on the properties of the scattered, fluorescent, and corpuscular radiations, as well as on the polarization, interference, reflection, and the velocity of X-rays. These seem to establish the theory that X-rays are merely light-waves of exceptionally short wave-length. Previous to the recent experiments on interference, one of the most significant properties which Röntgen rays had been shown to possess was that of polarization. Barkla, as early as 1906, showed that it was possible to produce a secondary beam of X-rays which shows fairly complete polarization.

Up to the present all experiments on the rotation of the plane of polarization have been made using light of a wave-length of the order of that found in the visible spectrum. The results indicate that the magnitude of the rotation in quartz and other active substances varies inversely as some power of the wave-length. This power over a considerable portion of the spectrum examined is the square, but it does not hold over a wider range.

On the assumption that Röntgen radiation is merely light of exceptionally short wave-length, it seemed possible that a great rotation of the plane of polarization of X-rays might be obtained under suitable conditions.

The object of this present research, suggested by Professor Barkla, was to test directly whether anything corresponding to a rotation of the plane of polarization could be obtained with X-rays.

Apparatus.

The apparatus was essentially similar to that used in previous experiments on X-ray polarization. X-rays from the anticathode O of an X-ray tube passed through the slits S₁ and S₂ in lead screens on to the first radiator R₁: a portion of the rays scattered from this radiator passed through the slits S₃ and S₄ in further lead screens, on to the radiator R₂. At equal horizontal and vertical distances of

* Communicated by Prof. C. G. Barkla, F.R.S. The expenses of this research have been partly covered by a grant from the Royal Society.


Experiments on Polarized Röntgen Radiation.

The substance which was being tested as regards its power of rotating the plane of polarization was placed at XX, so that the secondary partially polarized beam of rays from R₁ passed directly through it before striking R₂. A full account of this apparatus and the conditions which it must satisfy is given in the original paper*, where it is demonstrated that while there is but little polarization in the primary beam, yet in the secondary beam there is a considerable amount of polarization. This follows from elementary considerations of the usual theory of scattering.

In the present experiment, the primary and secondary beams were horizontal. When this was the case, and both the radiators at R₁ and R₂ consisted merely of a scattering agent such as carbon, it was found that the horizontal tertiary beam passing into A₁ was of much greater intensity than the vertical tertiary beam passing into A₂. When, however, the carbon plate at R₂ was replaced by a plate capable of giving a preponderating characteristic radiation, which has been shown to be distributed equally in all directions†, the intensities of the radiation reaching the

Phil. Mag. 25, 792-802 (1913)
X-ray absorption spectroscopy and magnetism

These results clearly prove that no measurable rotation of the plane of polarization of X-rays is produced by a sugar solution which is active for light in the visible spectrum.

The interpretation of these results is not that a fundamental difference exists between X-rays and light, but the experiments rather indicate that the usual formulae which determine the relation between rotation and wave-length for light in the visible spectrum are quite inadequate when light of exceptionally short wave-length is concerned.

Absorption of polarized X-rays by iron in magnetized state.

It is legitimate to assume that the absorption of X-rays by an atom of any given substance must depend to a certain extent on two factors:—(1) the period of the X-radiation absorbed; (2) the natural period of vibration of the electrons within the atom.

In order to explain double refraction and other phenomena peculiar to crystalline substances, it is necessary to suppose that the period of vibration of the electrons is dependent on the direction of vibration with respect to the atomic system.

Now in a polarized beam of X-rays, the electrical vibrations are largely in one direction. Consider now such a beam being transmitted through iron in which, since it is unmagnetized, there is no regular orientation of the orbits of the electron in the system. If, now, the iron is magnetized, the orientation becomes more regular, and if absorption of X-radiation is dependent on the direction of its own electrical vibration relatively to that of rotation of the electron in the absorbing substance, it might be expected that there would be a considerable alteration in the absorption of the material. With such an idea in mind, the following experiment was tried.

A polarized beam of X-rays was passed through iron when unmagnetized, and later when magnetized. The absorption of the polarized beam was determined in each case. In the first experiment, the field produced was perpendicular to the sheet of iron absorbing and parallel to the direction of the X-rays absorbed. In the second part the field was perpendicular to the direction of the X-rays absorbed and parallel to the sheet of iron absorbing. The field was produced in the first instance by a coil of wire, and in the second case by a powerful horseshoe electromagnet. In each case a standardizing electrooscope was employed to allow for changes in the primary beam.

The results are given in tabular form.

<table>
<thead>
<tr>
<th>Magnetic field perpendicular to X-rays and parallel to iron sheet.</th>
<th>H = 30,000 gauss.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption by iron</td>
<td>Absorption by iron</td>
</tr>
<tr>
<td>unmagnetized.</td>
<td>magnetized.</td>
</tr>
<tr>
<td>68.0 per cent.</td>
<td>68.0 per cent.</td>
</tr>
<tr>
<td>67.2</td>
<td>67.0</td>
</tr>
<tr>
<td>20.1</td>
<td>20.3</td>
</tr>
<tr>
<td>20.5</td>
<td>20.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Magnetic field parallel to X-rays and perpendicular to iron sheet.</th>
<th>H = 320 gauss.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption by iron</td>
<td>Absorption by iron</td>
</tr>
<tr>
<td>unmagnetized.</td>
<td>magnetized.</td>
</tr>
<tr>
<td>53.0 per cent.</td>
<td>53.1 per cent.</td>
</tr>
<tr>
<td>31.7</td>
<td>31.0</td>
</tr>
<tr>
<td>31.7</td>
<td>32.4</td>
</tr>
<tr>
<td>31.8</td>
<td>31.9</td>
</tr>
</tbody>
</table>

Thus the absorption of a polarized beam of X-rays by iron is not appreciably dependent upon whether it is magnetized or unmagnetized; that is, absorption of X-rays is independent of the orientation of the electronic orbits inside the atom, so far as they are affected by the magnetic state.
X-ray Absorption Spectroscopy and Magnetism

Phys. Rev. 3 (1914) 306-313

A. H. Forman.

The effect of magnetization on the opacity of iron to Röntgen rays.

In a general way it would seem natural to expect that a change in the molecular arrangement of iron by magnetization, which produces the phenomenon of magnetostriction, should to some extent also affect the opacity of the iron to Röntgen rays. The investigations along this line have all given negative results. Experiments in which the polarized secondary rays were used instead of the ordinary Röntgen rays have been tried with negative results.

Phys. Rev. 7 (1916) 119-124

Vol. VII, No. 1

Opacity of iron to Röntgen rays.

In a previous paper the results covering the investigation of the effect of magnetizing the iron in a plane perpendicular to the path of the Röntgen rays were published. The results were negative with a set up of apparatus sensitive enough to detect a change of one part in ten thousand under the most favorable conditions.
THE EFFECT OF A MAGNETIC FIELD ON THE ABSORPTION OF X-RAYS

By Joseph A. Becker

ABSTRACT

Effect of a magnetic field on the absorption of x-rays.—A continuation of previous work (Phys. Rev. 20, p. 134, 1922) with improved specimen holders and technique. Iron, aluminum, and carbon showed no changes in the absorption coefficient as great as one part in 10,000 (due to a magnetic field of 17,000 gauss) when the tube was operated at 90 kv peak. Carbon, wood, and lithium also showed effects smaller than the limit of accuracy of the apparatus—2 parts in 10,000 for 61 kv, 4 parts in 10,000 for 46 kv, and 10 parts in 10,000 for 30 kv. If the effect exists, then, it is very small.
In this work, an effect of a magnetic field on plane polarised X-rays scattered by Paraffin and Iron is studied. Far from the absorption edge the rotation can not be observed due the weakness of the rotation angle. Whereas at an absorption edge of ferromagnetic materials one can expect to measure the magnetic rotation eventhough precise measurements are very difficult.
Zeitschrift fur Physik, 52, 853-868 (1929)

On the scattering of radiation by free electrons according to the new relativistic quantum dynamics of Dirac

Über die Streuung von Strahlung durch freie Elektronen nach der neuen relativistischen Quantendynamik von Dirac.

Von O. Klein und Y. Nishina in Kopenhagen.

(Eingegangen am 30. Oktober 1928.)


Interaction between photons and magnetic electrons is considered for the first time

\[
\frac{d\sigma}{d\Omega} = \alpha^2 r^2_c P(E_\gamma, \theta)^2 \left[ P(E_\gamma, \theta) + P(E_\gamma, \theta)^{-1} - 1 + \cos^2(\theta) \right]/2
\]

\[
P(E_\gamma, \theta) = \frac{1}{1 + (E_\gamma/m_e c^2)(1 - \cos \theta)}
\]
Compton Scattering of 2.62-Mev Gamma Rays by Polarized Electrons\textsuperscript{*,†}

S. B. Gunst\textsuperscript{†} and L. A. Page

University of Pittsburgh, Pittsburgh, Pennsylvania

(Received July 20, 1953)

The differential cross section for Compton scattering of a circularly polarized photon by an electron with given initial spin orientation can be written as a sum of the common Klein-Nishina formula for no polarization and a term sensitive to polarization. The total cross section is $\sigma = \sigma_0 + \sigma_1$. A measurement of the transmission of 2.62-Mev gamma rays through iron magnetized along the transmission direction relative to that through unmagnetized iron gives the absolute value of $\sigma_1$ for this energy, if the number $\nu_0$ of polarized electrons per iron atom at saturation is known. For $\nu_0 = 2.06$, $\sigma_1/\pi r_0^2 = 0.089\pm0.007$. This agrees with the theoretical value 0.093. Alternatively, the theoretical $\sigma_1$ and the measurements would yield $\nu_0 = 1.97\pm0.15$.

The application of the method of this experiment to measurement of gyromagnetic ratios for ferromagnets is suggested, as is its application to the analysis of circularly polarized radiation.

Magnetic Scattering of X Rays from Electrons in Molecules and Solids

P. M. Platzman
Bell Telephone Laboratories, Murray Hill, New Jersey

and

N. Tzoar\textsuperscript{*}

City College of the City University, New York City, New York

(Received 2 June 1970)

The scattering of moderately high-energy x rays from electrons in magnetic solids is analyzed. We show that (a) the incoherent Compton scattering of polarized x rays can be used to determine the spin-dependent momentum distribution function of electrons in ferromagnetic materials, and (b) the coherent Bragg scattering of unpolarized x rays can be used to determine the magnetic structure of antiferromagnetic solids below their transition temperature.
OBSERVATION OF MAGNETIC SUPERLATTICE PEAKS BY X-RAY DIFFRACTION ON AN ANTIFERROMAGNETIC NiO CRYSTAL

F. De BERGEVIN and M. BRUNEL

Laboratoire de rayons-X, Cédex 166, 38–Grenoble-Gare, France

Received 14 February 1972

We observe on a NiO single crystal two superlattice X ray diffraction peaks, which disappear above the Néel point. Their intensities, $4 \times 10^{-8}$ smaller than normal ones, agree with those evaluated from photon-electron spin interaction.

Fig. 1. Intensity $I_t(\theta)$ near the $(\frac{1}{2}\frac{1}{2}\frac{3}{2})$ position at $t = 25^\circ$ C and $275^\circ$ C in counts/225 min. The hump which cover the interval could be due to some impurity.

Fig. 2. Intensity $I_t(\theta)$ near the $(\frac{3}{2}\frac{3}{2}\frac{3}{2})$ position at $t = 25^\circ$ C and $290^\circ$ C in counts/225 min.
**Etude de la Polarisation Circulaire du Rayonnement Synchrotron dans la Gamme des Rayons X par Diffraction sur un Composé Ferrimagnétique**

PAR M. BRUNEL, G. PATRAT ET F. DE BERGEVIN

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ET F. ROUSSEAUX* ET M. LEMONNIER

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### Conclusions

Malgré l'imprécision des résultats due, d'une par à la durée limitée des expériences, d'autre part aux instabilités du faisceau, nous avons pu montrer l'intérêt de la diffraction magnétique pour l'étude de la polarisation circulaire d'un faisceau de rayons X de longueur d'onde voisine de 1 Å. Les résultats sont cohérents, à la fois avec les calculs de polarisation circulaire du rayonnement synchrotron, et avec les calculs de diffraction magnétique des rayons X. L'utilisation du rayonnement synchrotron pour des études de structure magnétique pourrait être complémentaire de la diffraction neutronique, en particulier dans le cas des corps absorbant trop les neutrons (Gd par exemple) ou dans le cas où l'effet du moment orbital est difficile à séparer de celui du moment de spin (ces deux effets ne se combinent pas de la même façon pour les rayons X et les neutrons); toutefois elle semble limitée par la faible précision que l'on peut atteindre actuellement.
Basics of XMCD

The first serious approach to the problem of absorption of circularly polarized X-rays

Calculation of the $M_{23}$ magneto-optical absorption spectrum of ferromagnetic nickel

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E. A. Stern†

Department of Physics, University of Washington, Seattle, Washington 98195

(Received 28 April 1975)

The $M_{23}$ magneto-optical absorption spectrum of ferromagnetic nickel is calculated using an approach similar to the component state-density method that has been successfully used in obtaining valence-band emission and absorption x-ray spectra of metals. The $M_{23}$ magneto-optical effects result predominantly from spin-orbit splitting of the $3p$ core state in conjunction with the final $d$-state spin polarization. The calculated spectrum exhibits features that are directly related to electronic structure parameters including the $3p$ core spin-orbit splitting, and the unfilled $d$-band spin polarization. Temperature variations in the magneto-optical structure can be used to determine separately the exchange-splitting variation and spin-wave excitation contributions to the decrease in the magnetization. Experimental verification of these predictions should provide insight into the applicability of the Stoner model to ferromagnetic nickel and may be helpful in resolving some of the apparently conflicting results of other experimental probes of the spin polarization near the Fermi level in nickel.

Two-step model
Basics of XMCD

Two Step Model of XMCD

Absorption of a right circularly polarized photon

\[ |m_p, m_s, \Delta m_l = +1, \Delta m_s = 0 > \]

\[ |1, \uparrow > + \sqrt{3/3} |0, \uparrow > + \sqrt{3/3} |-1, \uparrow > + |0, \downarrow > + \sqrt{3/3} |1, \downarrow > \]

\[ \langle l_z \rangle = +3/4; \quad <\sigma_z> = 1/4 \]

\( L_{III} \)-edge (2p\(_{3/2}\))

\[ |m_p, m_s, \Delta m_l = +1, \Delta m_s = 0 > \]

\[ \sqrt{3/3} |1, \downarrow > + \sqrt{3/3} |0, \downarrow > - \sqrt{3/3} |-1, \uparrow > - \sqrt{3/3} |0, \uparrow > \]

\[ \langle l_z \rangle = +3/4; \quad <\sigma_z> = -1/2 \]

\( L_{II} \)-edge (2p\(_{1/2}\))

Excited photoelectrons are spin polarized
Two Step Model of XMCD

Exchange splitting of the valence band is driving the second step
First experimental evidence of influence of magnetism on X-ray absorption

**Basics of XMCD**

**First experimental evidence of influence of magnetism on X-ray absorption**

Strong Magnetic Dichroism Predicted in the $M_{4,5}$ X-Ray Absorption Spectra of Magnetic Rare-Earth Materials

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Physical Chemistry Department of the Materials Science Center, University of Groningen, 9747 AG Groningen, The Netherlands

(Received 21 August 1985)

A theory is presented which predicts an anomalously large magnetic dichroism in the $M_{4,5}$ x-ray absorption-edge structure of rare earths in magnetically ordered materials. Polarized synchrotron radiation can therefore be used to determine accurately the magnitude, the orientation, and the temperature and magnetic field dependence of the local rare-earth magnetic moment in a large variety of magnetically ordered materials and thin films.

PACS numbers: 78.20.Ls, 78.70.Dm

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**Experimental proof of magnetic x-ray dichroism**

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(Received 24 April 1986)

What we believe to be the first experimental results have been obtained on strong magnetic x-ray dichroism in the $M_{4,5}$ absorption spectra of magnetically ordered rare-earth materials, in accordance with recent predictions.

FIG. 1. Experimental $M_5$ absorption spectra of ThIG at various values of $\alpha$, which is the angle between the polarization vector of the x rays and the [111] magnetization direction. The solid lines are fits using Eq. (5). The optimum values of $C$ are indicated.
Absorption of Circularly Polarized X Rays in Iron

G. Schütz, W. Wagner, W. Wilhelm, and P. Kienle

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and

R. Frahm and G. Materlik

Hamburger Synchrotronstrahlungslabor am Deutsches Elektronen-Synchrotron DESY, D-2000 Hamburg 52, West Germany

(Received 22 September 1986)

The transmission of synchrotron radiation through magnetized iron at energies above the K-absorption edge shows relative differences for right and left circular polarization of several times $10^{-4}$. The observed spin dependence of the near-edge photoabsorption is proportional to the difference of the spin densities of the unoccupied bands. In the extended absorption region up to 200 eV above the Fermi level a small spin-dependent absorption is observed and thus is expected to give information on the magnetic neighborhood of the absorbing atom.

PACS numbers: 75.50.Bb, 75.10.Lp, 75.25.+z, 78.70.Dm
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The first Fe K-edge XMCD spectrum
Rapid Communications

Soft-x-ray magnetic circular dichroism at the $L_{2,3}$ edges of nickel

C. T. Chen, F. Sette, Y. Ma, and S. Modesti

AT&T Bell Laboratories, Murray Hill, New Jersey 07974

(Received 2 March 1990)

Magnetic circular dichroism (MCD) has been observed at the $L_{2,3}$ absorption edges of ferromagnetic nickel by use of circular-polarized soft-x-ray synchrotron radiation. The MCD intensity ratio between the $L_2$ and the $L_1$ edges is found to differ appreciably from that predicted by a simple exchange-split-valence-band model. Fine MCD features, imperceptible in the absorption spectra, are also observed and a tentative interpretation is given. This work, demonstrating the feasibility of MCD measurements in the soft-x-ray region, provides a new approach to study $3d$ and $4f$ ferromagnetic systems with their respective dipole-permitted $2p \to 3d$ and $3d \to 4f$ transitions.
XMCD Sum Rules

Sum rules relate experimental XMCD spectra to the spin and orbital moments.

**Orbital sum rule**

\[ \int (\mu^+ - \mu^-) = \frac{2I(l+1)}{l(l+1) + 2 - c(c+1)} \times C \times \langle L_z \rangle \]

**Spin sum rule**

\[ \int (\mu^+ - \mu^-) = C \times [A \langle S_z \rangle + B \langle T_z \rangle] \]

**Equivalent formula**

\[ T = \sum_i (s_i - 3r_i(r_i \cdot s_i)/r_i^2) \]

\[ C = \frac{1}{n_h} \int (\mu^+ + \mu^- + \mu^0) \]

- X-ray absorption cross section per hole;

\[ A = \frac{l(l+1) - 2 - c(c+1)}{3c} \]

\[ B = \frac{l(l+1)[l(l+1) + 2c(c+1)+4] - 3c(c-1)^2(c+1)^2}{6c \cdot l(l+1)} \]
\[ \langle L_z \rangle = -\frac{4}{3} \cdot C \cdot (A + B) \]
\[ \langle S_z \rangle - 7 \langle T_z \rangle = -2C \cdot (A - 2B) \]
\[ \frac{\langle L_z \rangle}{\langle S_z \rangle - 7 \langle T_z \rangle} = \frac{2}{3} \cdot \frac{(A + B)}{(A - 2B)} \]

*in the case of L\(_{3,2}\) absorption edges*

\[ C = \frac{(n^{Pt}_h - n^{Au}_h)}{A} \]

\( A \sim \) integrated intensity of transitions into unoccupied \( d \) band

\( d^h n \) = number of holes in \( d \) band

\[ \langle T_z \rangle \ll \langle S_z \rangle \]

(if S.-O. is small)
XMCD Sum Rules

\[ \langle L^p_Z \rangle + \epsilon \langle L^d_Z \rangle = -C \Delta K \]

\[ (E1-E1) \quad (E2-E2) \]

\[ C = \frac{n_{4p} + n_{3d}}{A_{4p} + A_{3d}} \]

- A \sim \text{integrated intensity of transition into unoccupied states}
- n \sim \text{number of holes}

\[ \Delta K \]

Photon Energy (keV)

XAS Intensity (a.u.)

Co K-edge

1s \rightarrow 4p

\text{hcp Co metal}

H=6\text{Tesla}

T=300\text{K}
LETTER TO THE EDITOR

Magnetic absorption dichroism and sum rules in itinerant magnets

P Strange
Physics Department, Keele University, Staffs ST5 5BG, UK

of the electrons in the dipole allowed states. This has proved to be a very useful and enlightening step forward in our understanding. However, there are still several questions to be answered. Firstly, the orbital and spin magnetic moments are energy integrated quantities, but the dichroism curves are often highly structured [5–7] and so the sum rules do not extract all the information from a dichroism experiment. Secondly, the models used

\[ \Delta \mu_{L3}(E - E_0) + \Delta \mu_{L2}(E - E_0) \approx \frac{\partial}{\partial E} \langle L_z \rangle_d \]

\[ \Delta \mu_{L3}(E - E_0) - 2\Delta \mu_{L2}(E - E_0) \approx \left[ \frac{\partial}{\partial E} \langle S_z \rangle_d + 7 \frac{\partial}{\partial E} \langle T_z \rangle_d \right] \]
Crystal field split 4d states of Y are strongly spin polarized with zero moment

\[ M_S \sim -0.001 \mu_B; \quad M_L \sim 0.0001 \mu_B \]

**YIG Thin Film**

\[ T = 300K \]
\[ H = 0.5T \]

**XAS**

**XMCD * 10**

**Y 4d DOS**

\[ 2p \rightarrow nd \text{ cross-section} \]
\[ l_z \]
\[ 2s_z \]
RESULTS

• Ni magnetic moments:
  \( \mu_{S}^{3d} = 0.35 \mu_{B}/\text{atom} \)
  \( \mu_{L}^{3d} = 0.038 \mu_{B}/\text{atom} \)

• Pt induced magnetic moments:
  \( \mu_{S}^{5d} = 0.14 \mu_{B}/\text{atom} \)
  \( \mu_{L}^{5d} = 0.03 \mu_{B}/\text{atom} \)

\( \text{Ni}_{2}/\text{Pt}_{2} \text{ multilayer} \)

\( T \sim 10K \)
\( H = \pm 5 \text{ T} \)

Sensitivity of XMCD

\[ <S_z> = 0.0353(5) \mu_B \quad <L_z> = 0.0054(5) \mu_B \] (per Au atom)

To compare with 4.15 \mu_B per Mn atom
Co$_{17}$/Pt$_7$/Gd$_{16}$/Pt$_7$ multilayer

Magnetization (a.u.)

G. Suciu et al., JMMM 240, 229 (2002).

H = 0 T

H = 7 T
Quantity to measure: $\Delta \mu = \mu^+ - \mu^-$

$\mu^+, \mu^- \Rightarrow$ Absorption cross-sections for CP X-rays with
(+ ) helicity parallel to the sample magnetization
(- ) helicity antiparallel to the sample magnetization

- Highly performing X-ray detectors
- Magnetic field to magnetize a sample
- Source of monochromatic circularly polarized X-rays

The best possible at the 3rd generation synchrotron radiation facilities
ESRF Beamline ID12

**Fixed exit Double Crystal Monochromator**

- **Undulator sources** 2.0 - 15 keV
- **Slits**
- **HFM-HDM**
- **Attenuator**
- **QWP**
- **Si (111)**
- **35 elements SDD**
- **Slits**
- **H < ±0.7 T (1Hz)**
- **T > 10 K**
- **XNCD/XNLD**
- **I_02**
- **I_f**
- **I_f^1-8**
- **XMCD on soft magnetic materials**
- **T > 20K**
- **H < 0.9 T**
- **XMCD on nanostructures**
- **I_f**
- **I_04**
- **Microwave pump**
- **XDMR**
- **T > 2.2 K**
- **High field XMCD**
- **I_f**
- **T > 10K**
- **H ~ 0.5 T (1Hz)**
- **generated by a set of permanent magnets**
- **I_01**
- **Reflecto/diffractometer XRMS**
- **I_f**
- **I_R**
- **θ_B < 18°**
- **T > 5 K**
- **H < ±6 Tesla**
- **H < ±17 Tesla**

**Multi-pinholes device**
ESRF Beamline ID12

Flux of circularly polarized X-rays (ph/s)

Photon Energy (keV)

pinhole 0.5(H)x0.4(V) mm² @ 30m

<table>
<thead>
<tr>
<th></th>
<th>APPLE-II</th>
<th>HELIOS-II</th>
<th>EMPHU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>38 mm</td>
<td>52 mm</td>
<td>80 mm</td>
</tr>
<tr>
<td>N</td>
<td>42</td>
<td>31</td>
<td>20</td>
</tr>
<tr>
<td>Min. Gap</td>
<td>16.2</td>
<td>5.7</td>
<td>16.2</td>
</tr>
<tr>
<td>Bₓ max</td>
<td>0.483 T</td>
<td>0.493 T</td>
<td>0.194 T</td>
</tr>
<tr>
<td>Bᵧ max</td>
<td>0.3 T</td>
<td>0.367 T</td>
<td>0.177 T</td>
</tr>
<tr>
<td>K max circ</td>
<td>1.28</td>
<td>2.52</td>
<td>1.13</td>
</tr>
<tr>
<td>1ˢᵗ harm</td>
<td>5 – 9.1 keV</td>
<td>1.55 - 6.2 keV</td>
<td>1.6 - 4.35 keV</td>
</tr>
<tr>
<td>Power</td>
<td>0.96 kW</td>
<td>0.77 kW</td>
<td>0.53 kW</td>
</tr>
<tr>
<td>Brilliance</td>
<td>6.2 ⋅ 10¹⁹</td>
<td>2.6 ⋅ 10¹⁹</td>
<td>1.0 ⋅ 10¹⁹</td>
</tr>
<tr>
<td>Reversal time</td>
<td>~ 5 sec</td>
<td>~ 5 sec</td>
<td>0.16 sec</td>
</tr>
</tbody>
</table>

European Synchrotron Radiation Facility
**Helios-II Undulator source**

31 periods

\[ \lambda_u = 52 \text{ mm} \]

\[ \text{thg} = 6.0 \text{ mm} \]

\( B_x = 0.349 \text{ T} \)

\( B_z = 0.493 \text{ T} \)

\[ \text{bhg} = 6.0 \text{ mm} \]

\[ E_{1 \text{ min}} = 1.7 \text{ keV}, \ E_{1 \text{ max}} = 6.2 \text{ keV} \]

Flux: \( 10^{14} \text{ ph/s/0.1%bw} \)

*Full control of polarization: flipping time ~ 5 seconds*

\[ B_x = B_z \]

**PHASE**

- \( \lambda_u / 4 \)
- 0
- \( \lambda_u / 4 \)
- \( \lambda_u / 2 \)

XMCD experiment at ID12

2.05 keV - 15 keV

K - edge
L - edges
M - edges
High Field Magnet

Magnet is a solenoid consisting of 3 coils (2 of Nb3Sn and outer of NbTi). The maximum field is 17T with homogeneity over 10mm DSV of 0.1%. Maximum ramp rate is 2Tesla/minute. Cryogens autonomy is about 48 h.
High field XMCD set-up
Magnetism in DMS

Semiconductor materials that are claimed to exhibit hysteresis and spontaneous magnetisation at 300 K

wz-c-(Ga,Mn)N, (In,Mn)N, (Al,Mn)N, (Ga,Cr)N, (Al,Cr)N
(Ga,Fe)N, (Ga,Cu)N, (Ga,Gd)N, (Ga,Eu)N
(Ga,Mn)As, (In,Mn)As, (Ga,Mn)Sb, (Ga,Mn)P:C
(Zn,Mn)O, (Zn,Ni)O, (Zn,Co)O, (Zn,V)O, (Zn,Fe,Cu)O, (Zn,Cu)O
(Ti,Co)O₂, (Ti,V)O₂, (Ti,Cr)O₂, (Sn,Co)O₂, (Sn,Fe)O₂, (Hf,Co)O₂
(Cd,Ge,Mn)P₂, (Zn,Ge,Mn)P₂, (Cd,Ge,Mn)As₂, (Zn,Sn,Mn)As₂
(Ge,Mn), (Ge,Cr), (Ge,Mn,Fe)
(La,Ca)B₆, C, C₆₀, HfO₂, TiO₂-K

XMCD has demonstrated that non of them is intrinsically ferromagnetic at RT

Magnetism in DMS

GaN : Mn

The most controversial diluted magnetic semiconductor

SQUID magnetometry measurements:

- **Ferromagnetism** \(2K < T_C < 940K\)


- **Paramagnetism**

A. Wolos et al., PRB 69, 115210 (2004)
Magnetism in DMS

What do we need to know more?

1. How are 3d atoms incorporated in the lattice?
   - Single phase
   - Presence of (magnetic) secondary phases
   - Clusters formation

Concentration limit?

2. What is the site of 3d atoms?
   - Substitution
   - Interstitial
   - Substitution and interstitial

3. What is the valence state of 3d atoms?

4. Is it really a diluted magnetic semiconductor or ferromagnetic clusters in semiconducting matrix?

Space group 186
Structure: P6₃mc
Non-centrosymmetric
Magnetism in DMS

Hard X-ray Dichroisms

Structural characterization

Linearly polarized X-rays

\[ \text{XLD} = \mu^\perp(E) - \mu^\parallel(E) \]

XLD measures the anisotropy of the unoccupied density of states at absorbing atom

• high sensitivity to local environment (symmetry, bonding, electronic structure)

Magnetic characterization

Circularly polarized X-rays

\[ \text{XMCD} = \mu^R(E) - \mu^L(E) \]

XMCD measures amplitude and directions of the spin and orbital moments carried by absorbing atom

• element selective magnetization measurements

![Diagram showing XLD and XMCD measurements](image-url)
Our GaMnN samples

Samples were grown by plasma assisted molecular beam epitaxy (PAMBE)

E. Sarigiannidou*, E. Monroy and H. Mariette
Equipe mixte CEA-CNRS-UJF “Nanophysics and Semiconductors”, DFRMC/SP2M CEA, Grenoble, France
*LMGP/LTM, INP -Minatec, Grenoble, France

Ga$_{1-x}$Mn$_x$N epitaxial film (400nm)

Homogeneous Incorporation of Mn from 0.04 up to max. 6.3 at.%
**Magnetism in DMS**

**Standard Macroscopic Characterization**

- **in-situ RHEED**
  - monitoring the growth

- **High Angle X-ray Diffraction**
  - detection limit of ~1\% of sample volume
  - absence of secondary phases
  - difference in the lattice parameter
  - not sensitive to amorphous phases

- **SQUID**
  - measure the whole sample including substrate, cap layer, inclusions, impurities
  - non trivial extraction of a true magnetic response
Magnetism in DMS

Macroscopic Magnetic Characterization

Magnetic Field \( \perp \) \( c \) crystal axis

Corrections from the diamagnetic/paramagnetic contribution: measurements on a blank substrate

Easy axis \( \Rightarrow \) in-plane

- Opening of the hysteresis loop at 2 K
  - Coercive Field \( \approx 100 \) Gauss

- Thermal Variation \( \Rightarrow \) \( T_C = 8 \) K

- Remanent magnetization 44% of the spontaneous magnetization \( \Rightarrow 2.4 \mu_B \) per Mn
Magnetism in DMS

X-ray Linear Dichroism (XLD) Results

- Mn atoms are Ga substituted
- No secondary parasitic or clusters phases

Magnetism in DMS

X-ray Linear Dichroism (XLD) Results

- All the Mn K-edge XANES spectra have similar spectral shape
  - small differences are observed at the first pre-edge peak (narrowing of 3d band)

- XLD spectra are identical for all samples from 0.04% up to 6.3% of Mn
  - No secondary parasitic or clusters phases
    - 0.04% Mn is the reference spectrum (presence of secondary phases is unlikely)

Mn is perfectly incorporated up to at. concentration of 6.3%
Magnetism in DMS

**X-ray Magnetic Circular Dichroism Results**

**XMCD Mn K-edge:**
probes the orbital magnetization

Large Signal (~ 1.4%) ➔ Large Orbital magnetic moment ➔ mainly Mn$^{3+}$

XANES of Mn in GaMnN at higher energy: different electronic structure

Presence of two pre-edge peaks ⇒ Mn$^{3+}$

Difference in XMCD:

1. Mn ($d^5$) in MnAs is $±0.2\%$ and integral is nearly zero

2. Mn ($d^{5+δ}$) in GaMnAs is $+0.25\%$ and positif

3. Mn in GaMnN is $-1.4\%$ and negatif

**mainly Mn$^{3+}$ ($d^4$)**
**W induced magnetic moments:**

\[
\mu_S^{5d} = -0.33 \mu_B \quad \mu_L^{5d} = 0.12 \mu_B 
\]

**Ferrimagnetic ordering in both compounds**

\[
\mu_S^{5d} = -0.22 \mu_B \quad \mu_L^{5d} = 0.1 \mu_B 
\]

\[T_C=\text{443K} \]

\[T_C=\text{160K} \]

**Induced magnetism**

[Fe₅/W₃]₃₀ multilayer  \hspace{1cm} Fe₀.₉₇W₀.₀₃ thin film


In collaboration with E. Majkova (Slovakia)

**W induced magnetic moments are different in the multilayer and in the alloy**
Induced magnetism

\[
\begin{align*}
M_{\text{spin}}^{W-5d} &= -0.17 \, \mu_B/\text{atom} \\
M_{\text{orbital}}^{W-5d} &= -0.015 \, \mu_B/\text{atom} \\
M_{\text{tot}}^{W-5d} &= -0.185 \, \mu_B/\text{atom} \\
M_{\text{orbital}}^{W-5d}/M_{\text{spin}}^{W-5d} &= +0.09 \\
M_{\text{spin}}^{W-5d} &= -0.70 \, \mu_B/\text{atom} \\
M_{\text{orbital}}^{W-5d} &= +0.03 \, \mu_B/\text{atom} \\
M_{\text{tot}}^{W-5d} &= -0.67 \, \mu_B/\text{atom} \\
M_{\text{orbital}}^{W-5d}/M_{\text{spin}}^{W-5d} &= -0.043
\end{align*}
\]

Dimensionality may break even the well-established atomic rules (third Hund's rule)
Induced magnetism

Who Breaks the Third Hund’s Rule?

- Charge transfer $5d$ W ↔ $3d$ Fe

**Multilayer Fe/W:** $n_{h}^{W-5d} = 6.11$ holes

$n_{h}^{5/2} / n_{h}^{3/2} = \boxed{3.17}$

**Alloy Fe$_{97}$/W$_{3}$:** $n_{h}^{W-5d} = 5.72$ holes

$n_{h}^{5/2} / n_{h}^{3/2} = \boxed{2.10}$

- Local symmetry: impurity vs interface

- Spin-other-orbit coupling

\[
J_{\text{inter}} \cdot S_{Z}^{Fe} \cdot S_{Z}^{W} \quad > \quad \lambda_{\text{inter}} \cdot S_{Z}^{Fe} \cdot L_{Z}^{W} \quad > \quad \lambda_{\text{intra}} \cdot S_{Z}^{W} \cdot L_{Z}^{W}
\]

Inter-atomic spin-spin coupling (antiferromagnetic coupling)

Inter-atomic antiferro Fe-W spin-other-orbit interaction

Intra-atomic W spin-orbit coupling (antiparallel) (third Hund’s rule)
**Induced magnetism**

**Magnetization Profile in Fe/W**

![Graph showing magnetization profile in Fe/W](image)

**Total Magnetic Moments (μB/atom)**

![Bar chart showing total magnetic moments](image)

![Graph showing photon energy vs asymmetry ratio](image)

Magnetism in Ga+ irradiated Pt/Co/Pt

Magneto-optical Kerr studies

Remanence $\theta_{REM}$

Effective anisotropy field $H_{1eff}$

$d_{Co} = 3.3$ nm

$D = 7 \times 10^{15}$ ions/cm$^2$

$D_2 = 4.6 \times 10^{15}$

$D_3 = 9.3 \times 10^{14}$

$D_4 = 3.1 \times 10^{14}$

$D_5 = 0$

$H_{eff}$ [kOe]
Magnetism in Ga+ irradiated Pt/Co/Pt

XMCD studies at the Cobalt K edge

PMA branches 1 and 2 are due to formation of a CoPt alloy at upper and lower interfaces, respectively.

Exchange coupling in multilayers

Indirect exchange coupling in Py/Cu/Pd system

Pd acquires a moment even through a 3nm thick Cu layer
Exchange coupling in multilayers

**A Probe of Magnetization Dynamics using XMCD**

**X-ray detection of magnetic resonance**

**Ferromagnetic Resonance:**

\[ \omega_{\text{res}} = \gamma H_{\text{eff}} = \gamma (H_0 - 4\pi M_S \Delta N); \gamma \approx 28 \text{ GHz/T} \]

- **Microwave Pump Field**
- **Static Bias Field**
- **Transverse Probe**
  - XMCD \( \propto \Delta M_\perp \)
- **Longitudinal Probe**
  - XMCD \( \propto \Delta M_z \)
  - Steady-state + 2\(^\text{nd}\) Harmonic

**CP X-rays**
- Modulated at Microwave Frequency

**Small Precession angle \( \phi_0 \)**
- High Microwave Pumping Power Required !..

**Time-domain: Bunch structure**

\[ I_{xb}(t) = I_0 \sum_{N} \delta(t - N \cdot \Delta T) \otimes \frac{1}{\sigma \sqrt{2\pi}} \exp \left\{ -\frac{t^2}{2\sigma^2} \right\} \]

- ESRF: \( \delta t_{fwhm} = 2.35 \sigma = 50 \, \text{ps} \) \( \Delta T = 2.839 \, \text{ns} \)
- FT \( \text{cf. E. Gratton (1992)} \)

**Frequency domain: Harmonics**

\[ H_{xb}(F) = I_0 \cdot RF \sum_{N} \delta(F - N \cdot RF) \times \exp \left[ -2(\pi \sigma F)^2 \right] \]

- \( \sigma_F (\text{Freq. Distribution}) = (2\pi \sigma)^{-1} = 7.48 \, \text{GHz} \)
- \( F_{1/2} (\text{hwhm}) = 8.79 \, \text{GHz} \) \( (N = 25) \)
  - i.e. in the microwave X-band

**HETERODYNE DETECTION OF XDMR USING HARMONICS \( N \times RF \)**

...AS INTERNAL LOCAL OSCILLATOR

\[ \text{LO} = 24 \times RF = 8452.848 \, \text{MHz} \]
New tunable X-band TE_{102} microwave cavity for XDMR experiments
X-ray detection of magnetic resonance

**Unexpected Difficulty**

RF Frequency is an ADJUSTABLE parameter for Storage-Ring operation

- XDMR Signal shifts by 24 x 1 Hz at each re-adjustment
- Real-Time Correction of $F_{MW}$

**Transverse XDMR Signal**

- Corrected
- Uncorrected

- $F_{MW}$: 8452.146 MHz
- 24xRF: 8452.86328 MHz

**Oscillating at Microwave Frequency**

$\text{XMCD } \propto \Delta M_{\perp}$

**Transverse XDMR Signal**

- $H_0$
- $h_1$
- $M_s$
- $M_{eq}$

**Beating Frequency:** 718.223166 kHz

**Graphical Representation:**

- YIG Thin Film
- XDMR @ Fe K-Edge
- Transverse XDMR Signal

**Diagram Labels:**

- Beating Frequency (kHz)
- $10^\log \text{(Power Spectra) / dB}$
- $\beta''$

**Equations:**

- $J_0 \cdot M_s \cdot M_{eq}$
- $\mathbf{H}_0$
- $\mathbf{h}_1$
- $\theta_0$
- $\mathbf{M}_{eq}$

**Graphs:**

- Corrected and Uncorrected Power Spectra

**Legend:**

- Corrected
- Uncorrected

**Notes:**

- Super-Heterodyne Detection
X-ray detection of magnetic resonance

Super-Heterodyne Detection of XDMR Spectra

(a) YIG thin film Fe K-edge
- XDMR Absorptive part
- XDMR Dispersive part
- Magnetic Field (G)

MW Power 10 mW

(b) Photon Energy (eV)
- XDMR
- XMCD

7.5 G
To conclude

X-ray Magnetic Circular Dichroism is very powerful spectroscopic tool to unravel the microscopic origin of magnetism

BUT

XMCD is only a small part of the story …
THANK YOU