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Measurement of the Polarization of Extreme Ultraviolet Synchrotron Radiation with a Reflecting Polarimeter[§]

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Abstract

The polarization of extreme uv light provided by a normal-incidence monochromator used with synchrotron radiation from the 6 GeV electron synchrotron DESY has been measured. The measured polarization increases from 82 % at 500 Å to 87 % at 1000 Å and is in excellent agreement with the calculated polarization of the light incident upon the monochromator grating. A reflecting polarimeter consisting of a polarizer and an analyzer each made of four gold mirrors has been used in the measurement.

1. Introduction

Light with a high and precisely known degree of polarization is a powerful tool in many investigations. The synchrotron radiation from an electron synchrotron provides a highly polarized and intense source of extreme uv light for which the polarization can be calculated[1]. A normal-incidence grating monochromator has been constructed at the 6 GeV Deutsches Elektronen-Synchrotron (DESY) to utilize this polarized radiation in studies of the optical properties of solids. The monochromator has been described by Skibowski and Steinmann[2] and early experiments with it by Skibowski *et al*[3]. Though experiments with the monochromator[3] show conclusively that it provides almost completely polarized light the desire for a direct and precise measurement of the degree of polarization in the exit arm of the monochromator led to the work described here.

At wavelengths below the LiF transmission limit of 1050 Å no convenient polarizers exist[4]. The partial polarization produced by reflection near the polarizing angle can be used. Hamm *et al*[5], Ejiri[6], Uzan *et al*[7] and others have made use of polarization by reflection in the extreme uv. Polarimeters operating with the reflection principle have several disadvantages. The light intensity loss is great and the change in direction of the incident light caused by reflections can be troublesome. The loss of intensity cannot be overcome, but it is not serious if an intense source (for example, a synchrotron) is available. The disadvantage of direction change may be disposed of if enough mirrors can be used without too great an intensity loss. If one uses a polarizer-analyzer combination as suggested by Hamm *et al*[5] the polarization of incident light as well as the degree of polarization produced by the polarizers can be determined.

In section 2 we describe the operation and construction of a reflecting polarimeter consisting of eight gold mirrors and outline the procedure used to measure the polarization of the light produced by our synchrotron-monochromator combination. Section 3 contains the results of measurements and calculations for both the performance of the polarimeter and the degree of polarization of light produced by our monochromator using synchrotron radiation as a source.

2. Polarimeter

Figure 1 shows a sketch of our polarimeter. We briefly discuss the properties of a hypothetical polarimeter consisting of two "mirrors" which reflect light near the polarizing angle, but which do not change the direction of propagation of the incident light. The reflectances of "mirror" i for s and p light respectively we denote R_{si} and $R_{pi} = R_{si}\rho_i$ where $i = 1,2$. We choose a cartesian coordinate system with the z-axis in the direction of the beam. In our case the x-z plane is the synchrotron plane.

We let angles ϕ_i denote the rotation of the "mirrors" about the z axis. $\phi_i = 0$ is defined as that angle where light with its electric vector parallel to the x axis is incident on the "mirror" i with this vector perpendicular to the "mirror" plane of incidence. See Fig. 1a. The intensity incident upon the polarimeter is

$$I_o = |E_x|^2 + |E_y|^2. \tag{1}$$

The intensity of the light emerging from the polarimeter, $I(\phi_1, \phi_2)$, may be immediately written down for the following special cases:

$$I(0,0) = R_{s1} R_{s2}(|E_x|^2 + \rho_1\rho_2 |E_y|^2), \tag{2}$$

$$I(\tfrac{\pi}{2},\tfrac{\pi}{2}) = R_{s1} R_{s2}(\rho_1\rho_2 |E_x|^2 + |E_y|^2), \tag{3}$$

$$I(\tfrac{\pi}{2},0) = R_{s1} R_{s2}(\rho_1 |E_x|^2 + \rho_2|E_y|^2), \tag{4}$$

and

$$I(0,\tfrac{\pi}{2}) = R_{s1} R_{s2}(\rho_2 |E_x|^2 + \rho_1|E_y|^2). \tag{5}$$

R_{si} and ρ_i are a measure of the effectiveness of the polarizers. An ideal polarizer would transmit all of one component of the light and none of the other component (i.e., would have $R_s = 1$ and $\rho = 0$). We will call ρ^{-1} the "quality" q of a polarizer. Of special interest are the ratios:

$$i_I = \frac{I(\frac{\pi}{2}, \frac{\pi}{2})}{I(0,0)} = \frac{|E_y|^2 + \rho_1\rho_2|E_x|^2}{|E_x|^2 + \rho_1\rho_2|E_y|^2}, \tag{6}$$

$$i_{II,\ 1} = \frac{I(\frac{\pi}{2},0)}{I(0,0)} = \frac{\rho_1|E_x|^2 + \rho_2|E_y|^2}{|E_x|^2 + \rho_1\rho_2|E_y|^2}, \tag{7}$$

and

$$i_{II,2} = \frac{I(0,\frac{\pi}{2})}{I(0,0)} = \frac{\rho_2|E_x|^2 + \rho_1|E_y|^2}{|E_x|^2 + \rho_1\rho_2|E_y|^2}. \qquad (8)$$

By measuring these three ratios it is possible to determine the unknown quantities $|E_y|^2/|E_x|^2$, ρ_1 and ρ_2. As we show in section 3, it is possible to build a reflection polarizer with high q, i.e., with $\rho << 1$. In this case (as long as $\rho^2 << |E_y|^2/|E_x|^2 << \rho^{-2}$) Eqs. (6) - (8) become to an excellent approximation:

$$i_I = |E_y|^2 \;/\; |E_x|^2, \qquad (9)$$

$$i_{II,1} = \rho_1 + \rho_2\, i_I, \qquad (10)$$

and

$$i_{II,2} = \rho_2 + \rho_1\, i_I. \qquad (11)$$

We may therefore measure the polarization P of light incident on the polarimeter by simply measuring i_I, since

$$P = \left|\frac{|E_x|^2 - |E_y|^2}{|E_x|^2 + |E_y|^2}\right| = \frac{1 - i_I}{1 + i_I} \qquad (12)$$

Ratios $i_{II,1}$ and $i_{II,2}$ give a measure of the quality of the polarizers. For a polarimeter built of two identical polarizers $i_{II,1} = i_{II,2}$.

It has been pointed out that Au is a good material for producing polarization by reflection in the extreme uv[8,9/]. We have performed computer calculations of the reflectance of Au using the optical constants measured by Canfield *et al*[10/] for various angles of incidence. The calculations indicate that for angles of incidence near 60° Au has a relatively high R_s and low ρ as desired. Hamm *et al*[5/] have shown that a polarizer may be constructed of three Au mirrors with angles of incidence 80°-70°-80°. This polarizer does not change the direction of an incident light beam, but does invert it. Since our source, synchrotron light, and our detector, a Bendix M306 electron multiplier, are both inhomogeneous we required a polarimeter which neither inverts the beam nor changes the direction of propagation of the incident light. These desired properties have been achieved by constructing each of the two polarizers in our polarimeter from four Au mirrors. All are at an angle of incidence of 60° and have their normals in one plane. Each mirror-system is rotatable about the axis of the beam. Figure 1b shows a schematic drawing of the polarimeter. With our arrangement it is possible to choose for all four mirrors the most favourable angle of incidence. In this way we obtained polarizers of high quality.

The Au mirrors were prepared upon glass slides measuring 17 x 24 mm and 25 x 14 mm for polarizers 1 and 2 respectively. In order to obtain a high reflectance the mirror substrates were heated to 300° C during evaporation. The Au films 1500 Å thick were evaporated in a pressure of 10^{-6} torr at a rate of about 100 Å/sec. Each set of four mirrors is clamped in a solid frame. After assembly the mirror systems were adjusted with the help of a laser to give a minimal beam deviation upon rotation of their frames. The mirror frames were mounted in high vacuum in a holder which allowed rotation by remote control.

3. Results

The circles in Fig. 2 show the degree of polarization measured after the exit slit of our monochromator. The vertical lines give our error estimates. The errors originate mainly in the fluctuation of the synchrotron current and the electronic reference device we use to compensate for this fluctuation. The mean error of the measured degree of polarization is about 1 %. It was impossible to extend the measurement to wavelengths greater than 1000 Å because of the onset of the second order spectrum. Below 500 Å the low intensity transmitted by our monochromator and polarimeter precluded measurements. The maximum energy of the synchrotron during the measurements was 6.2 GeV. We had an angular aperture of 0.375 mrad for synchrotron light incident upon the grating. The aperture is located 40 m from the synchrotron electron orbit. The curves in Fig. 2 represent theoretical values. Calculations have been made on the basis of the data above for apertures lying symmetric (upper curve) and 5 mm asymmetric (lower curve) with respect to the synchrotron plane. The difference between the optimal calculated (symmetric position) and the measured polarization is less than 3 %.

The slight deviation between theory and this experiment may arise from the following influences:

a) The position of our aperture with respect to the plane of the synchrotron is only known to within approximately 3 mm.

b) Betatron oscillations and the finite diameter of the electron beam in the synchrotron reduce the polarization of the radiation in the synchrotron plane. These effects have

been observed in the visible light region by Codling and Madden[14/]. Even in the visible region, windows cause some depolarization and intensity distribution changes. For our work a windowless measurement was, of course, imperative.
c) Our Au coated grating is used in near-normal-incidence (angle of incidence < 9° for wavelengths < 1200 Å) which, according to calculations of the reflectance for an Au mirror, should change the degree of polarization of the incident synchrotron radiation by only ∿ 0.5 %. The grating structure may cause a slight additional depolarization.

Figure 3 shows the measured polarizing quality of both polarizers. A theoretical curve calculated from the Au optical constants[10/] is also shown. From 600 to 1000 Å the measured qualities remain nearly constant at about $q = 300$. From the theoretical values we would expect q's up to about 1000. We believe the lower values result mainly from misadjustment of the mirrors. If the normals of the four mirrors of one system do not lie exactly in one plane, a linearly polarized beam never falls as exact p- or s-light on all mirrors at once. Surface layers or roughness on the mirrors may also limit the polarizing quality. The deviations between our q calculations and measurements may stem in part from real differences between the optical constants used in the calculations and those of our mirrors. It should be noted that from a practical standpoint the flatness of our measured q's is a desirable characteristic of our polarizers, and also that any q >> 1 is very good.

The measurements described here allow us to make measurements of polarization dependent effects with our normal-incidence extreme uv monochromator with a known degree of polarization. In addition, they provide the first direct measurement of the polarization of the synchrotron radiation in the extreme uv. Corresponding measurements in the visible[11-14] and x-ray[15] regions of the spectrum have been performed earlier with other techniques.

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Footnotes

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Figure Captions

Fig. 1 Schematic representation of the reflection polarimeter

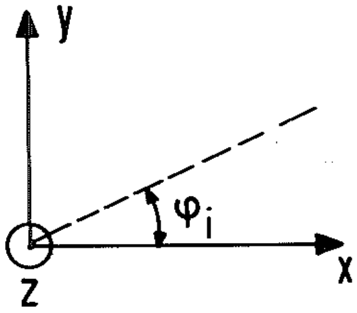
a) Angle definition

b) S-slit; P1, P2-polarizers; B-Bendix detector. Position $\phi_1 = \phi_2 = 90^\circ$

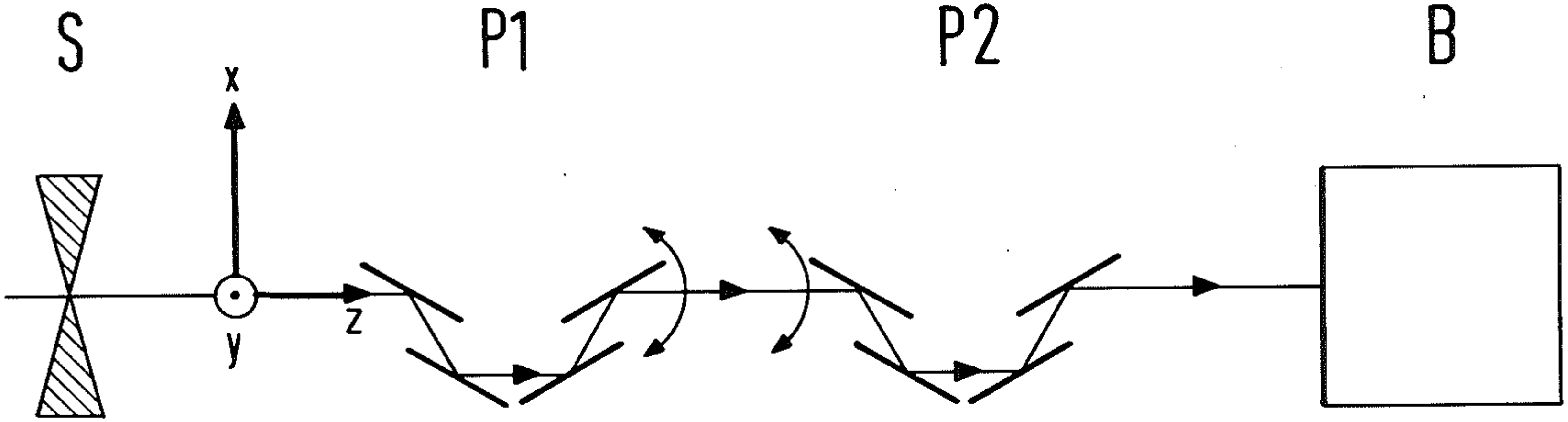
Fig. 2 ooo Measured polarization of the light produced by the normal-incidence monochromator. Calculated polarization of light incident upon monochromator grating: ——— symmetric aperture, -------- asymmetric aperture.

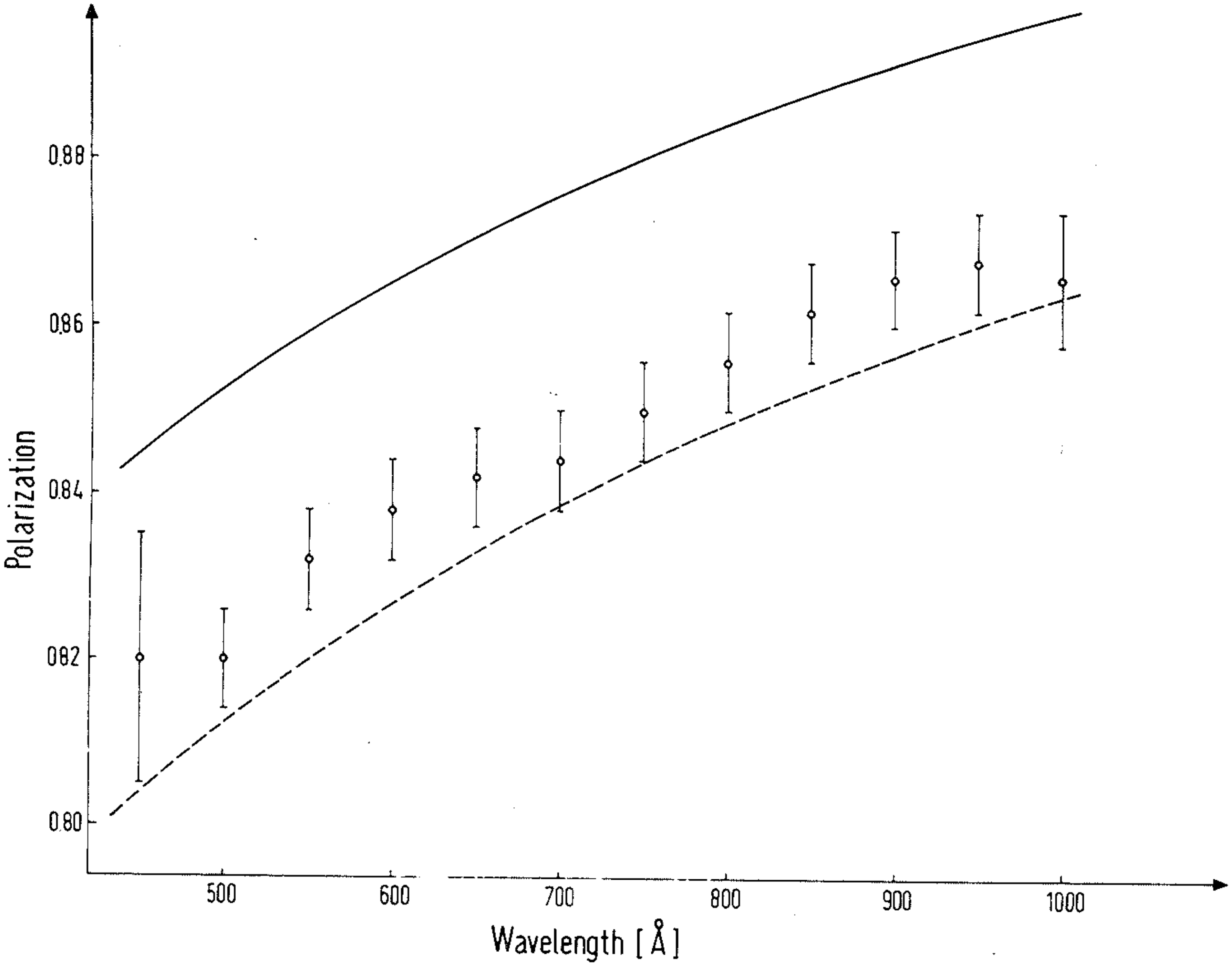
Fig. 3 Polarizing quality of the polarizers as a function of wavelength: - - - measured, ——— calculated.

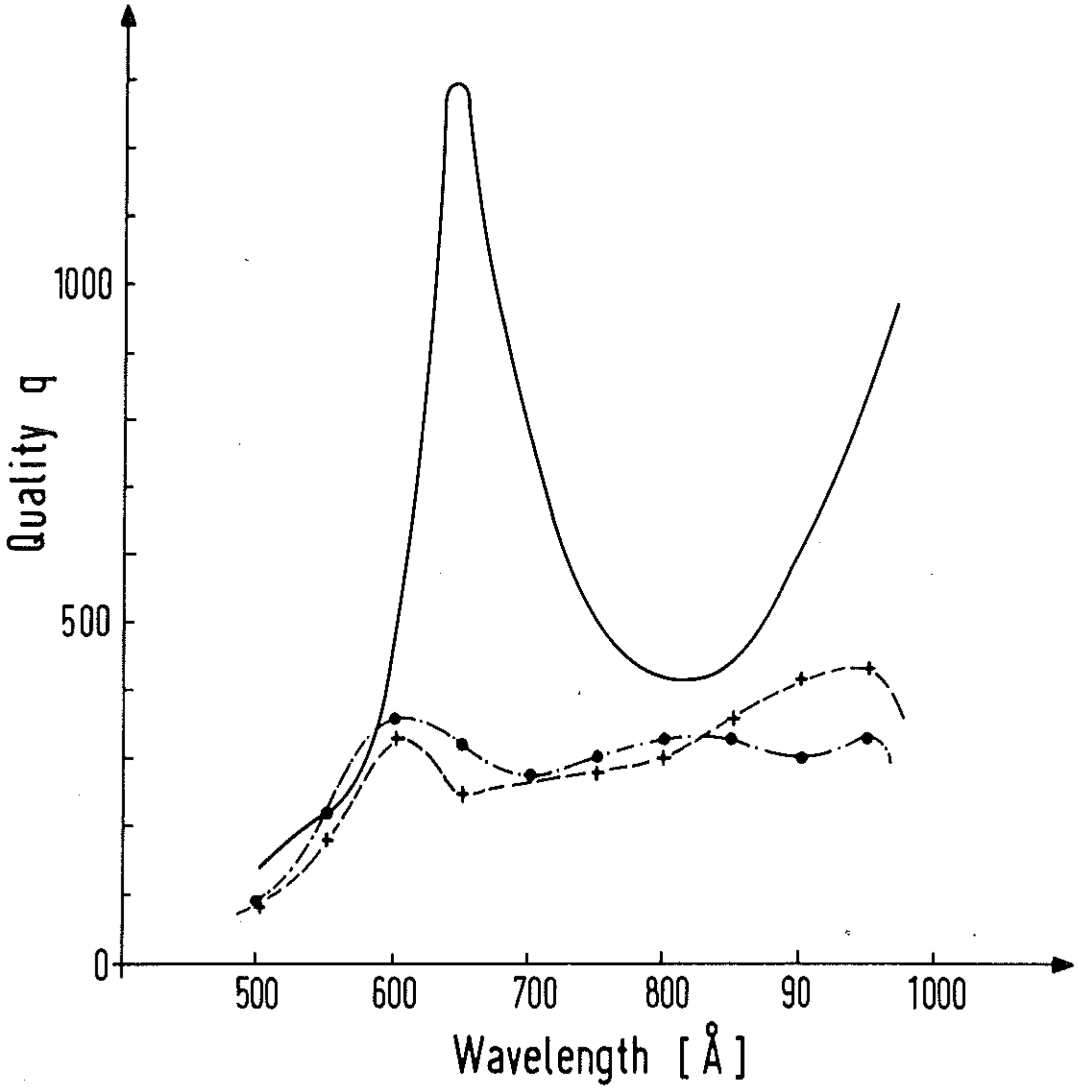
a)



b)




0.88
0.86
0.84
0.82
0.80
Polarization
500
600
700
800
900
1000
Wavelength [Å]


Quality q
1000
500
0
500
600
700
800
90
1000
Wavelength [Å]