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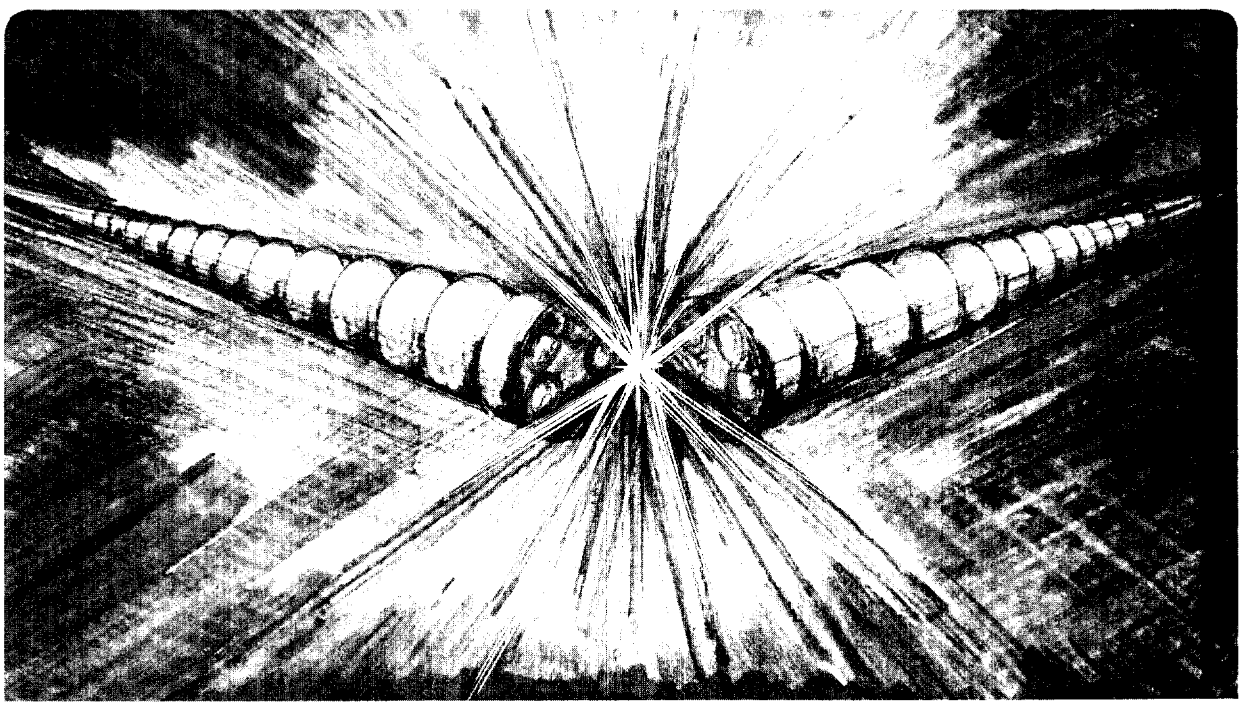

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POLARIZATION MEASUREMENT AND VERTICAL APERTURE OPTIMIZATION FOR OBTAINING CIRCULARLY POLARIZED BEND-MAGNET RADIATION*

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Polarization Measurement and Vertical Aperture Optimization for Obtaining Circularly Polarized Bend-Magnet Radiation

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Using multilayer linear polarizers, we have characterized the polarization state of radiation from bend magnet beamline 9.3.2 at the Advanced Light Source as a function of vertical opening angle at photon energies of 367 and 722 eV. Both a fine slit and a coarse semi-aperture were stepped across the beam to accept different portions of the vertical radiation fan. Polarimetry yields the degree of linear polarization directly, and the degree of circular polarization indirectly assuming an immeasurably small amount of unpolarized radiation based on the close agreement of the theoretical and experimental results for linear polarization. The results are in good agreement with theoretical calculations, with departures from theory resulting from uncertainty in the effective aperture of the measured beam. The narrow 0.037 mrad aperture on the orbit plane transmits a beam whose degree of linear polarization exceeds 0.99 at these energies. The wide semi-aperture blocking the beam from above and below transmits a beam with a maximum figure of merit, given by the square root of flux times degree of circular polarization, when the aperture edge is on the orbit plane thus blocking only half of the total available flux.

Growing interest in utilizing circular polarization has prompted the design of bend-magnet beamline 9.3.2 at the Advanced Light Source, covering the 30-1500 eV spectral region, to include vertical aperturing capabilities for optimizing the collection of circular polarization above and below the orbit plane [1]. After commissioning and early use of the beamline, a multilayer polarimeter [2] was used to characterize the polarization state of the beam as a function of vertical aperture position. This paper describes the polarimetry measurements and compares results with theoretical calculations intended to simulate experimental conditions.

Beamline 9.3.2 has three vertically deflecting optical elements, with incidence angles ranging from 1.2 to 2.5°, and variable aperture stops for polarization control just upstream of the first optic [1]. The upward focusing mirror M2 is followed by the downward deflecting spherical grating (600 lines/mm for these measurements) and the refocusing mirror M3. M2 defines the maximum vertical acceptance of the beamline as +/- 0.6 mrad, but the downstream grating and M3 may further limit the vertical aperture at certain grating focal conditions. When these measurements were made, M3 did not refocus at the polarimeter, and was short enough to act as an effective aperture at lower energies. M3 has since been replaced by a longer mirror with improved focal range that will not limit the vertical aperture. Polarimetry measurements used a movable vertical aperture stop just upstream of M2. This aperture consists of a cooled Cu plate with 0.5 mm and 25.4 mm wide slits displaced vertically to define narrow (0.037 mrad) and wide (1.9 mrad) vertical apertures. The narrow slit is much smaller than the vertical beam width, and is useful for measuring the vertical beam profile and selecting a narrow portion for experiments. The wide aperture can pass the entire beam when centered vertically, and is used as a semi-aperture to obscure the beam either from above or below. The aperture assembly is precisely positioned in the vertical direction through computer control. A second Cu plate just downstream of the first houses a second wide aperture, which together with the first allows selection of an arbitrary portion of the vertical radiation fan. All data reported here were collected at 1.9 GeV operation of the storage ring.

Polarization and intensity measurements as a function of the vertical aperture were made using a recently developed multilayer polarimeter [2]. Figure 1 shows a schematic of the polarimeter, which can utilize both a transmission multilayer phase retarder and a reflection polarizer or analyzer. Some recent polarimetry measurements using multilayers have used a retarder to help distinguish between possible unpolarized and circularly polarized radiation [3,4]. We did not utilize a retarder for these measurements, and have found the degree of unpolarized radiation to be immeasurably small (see below). Without a retarder we also loose the ability to distinguish between left and right circular polarization, which is not problematic for bend magnet radiation. Three multilayers with constant period were mounted on the polarizer stage, which could be translated to illuminate the different optics, enabling polarimetry measurements at 93 eV (Mo/Si multilayer), 367 eV (W/B_4C) and 722 eV (W/B_4C) without breaking vacuum. The polarimeter was mounted on a port of an endstation chamber which was grossly positioned to illuminate the polarimeter entrance aperture. Fine adjustment of the polarimeter was accomplished with its own translation and tilt stages. Because the polarimeter was not at a focus, the position of its 2 mm entrance pinhole was reoptimized as the upstream vertical aperture position was changed by vertical translation to maximize the flux through the pinhole.

Standard rotating analyzer ellipsometry techniques and expressions were used to collect and analyze data [5]. Data collected included the intensity entering the polarimeter, measured as a mesh current, and analyzer scans which record the intensity reflected from the polarizer as it rotates azimuthally about the beam direction. The reflected intensity normalized by the incident intensity as a function of azimuthal angle α is given by

$$I(\alpha) = S_0(R_s + R_p)/2 + 0.5(R_s - R_p)[S_1\cos(2\alpha) + S_2\sin(2\alpha)]$$

where R_s and R_p are reflectivities of s- and p-component radiation from the polarizer, and S_0, S_1 and S_2 are the first three of four Stokes parameters that define the intensity and polarization state of the beam. Thus we measure directly the degree of linear polarization, $P_L = (S_1^2 + S_2^2)^{1/2}/S_0$. For all measurements reported here, S_2, the linear component at +/- 45°, is negligible compared to S_1, the linear component at 0° and 90°. Circular polarization is represented by the fourth Stokes parameter, S_3, and the degree of circular polarization $P_C = S_3/S_0$. If there is no unpolarized radiation, then P_C is determined from $P_L^2 + P_C^2 = 1$. If the unpolarized component is non-zero, then $P_L^2 + P_C^2 < 1$. Since P_L and P_C add in quadrature, we can think of them as representing the amplitudes of different polarization types. Some confusion in the literature appears over usage of the terms degree and percent of linear(circular) polarization. Following the above convention, the degree of linear(circular) polarization is $P_L(P_C)$, while the percent of linear(circular) polarization is $100 \times P_L^2(P_C^2)$.

Polarimetry data taken as the narrow vertical aperture is stepped across the beam are useful to determine the orbit plane, to set an upper limit on the amount of unpolarized radiation, and to measure the variation of polarization state with aperture position. Since the radiation is most linearly polarized in the plane of the electron orbit, measuring P_L as the narrow aperture is scanned unambiguously determines the orbit plane. Using the maximum in an intensity measurement to determine the orbit plane can be misleading if the measurement is made downstream of optics that are poorly aligned with respect to the beam. Careful vertical alignment of each optical element in succession, using intensity signals, was conducted prior to polarimetry measurements presented below. After alignment, both intensity and polarization signals indicated that the optics were reasonably well centered on the beam.

Experimental and theoretical values for P_L and P_C vs. ψ at 367 and 722 eV are shown in Figure 2. Theoretical values are obtained by integrating standard expressions for bend magnet radiation [1,6] over the region of vertical opening angle ψ defined by the 0.037 mrad aperture. In comparing theory with experiment we assume that the incidence angles ($\leq 2.5°$) at the beamline optics introduce negligible changes in the beam's polarization. At each energy there is good agreement between measurement and theory out to large ψ values, confirming that the beamline optics are well aligned. A more rapid fall in P_L with ψ is evident at the higher energy, as expected. An upper limit to the degree of unpolarized radiation can be estimated from experimental data alone, by determining the most linearly polarized portion of the beam measured and assuming that the remaining portion is entirely unpolarized [7]. Assuming that this degree of unpolarized radiation is constant with ψ would then allow the determination of a lower limit to P_C even in the presence of possible unpolarized radiation. However, the theoretical calculations for a perfectly polarized source yield P_L values in excellent agreement with those measured, indicating that the remaining radiation is not unpolarized but rather is the small amount of circularly polarized radiation entering the narrow aperture because of its non-zero size. Thus in our experimental determination of P_C we assume zero unpolarized radiation, and believe that any unpolarized radiation present is smaller than the uncertainty in our measurement. With the narrow aperture at $\psi = 0$ the theoretical value for P_L is 0.9993 and 0.9991 for 367 and 722 eV, respectively.

We also investigated the polarization and flux response to obscuring the beam from above and below using the larger vertical semi-aperture. Figure 3 shows P_L, P_C and the fractional flux measured at two energies as a function of the semi-aperture position in the beam. Negative(positive) values of semi-aperture position correspond to obscuring the beam from above(below) to the ψ value indicated. Calculations are made over an angular aperture roughly corresponding to that measured, and have assumed an upper ψ limit of 0.6 and 0.5 mrad for 722 and 367 eV photon energies, respectively. At the lower energy the changing focal position of the spherical grating overfills M3, causing it to act as an effective aperture. The flux data are the fraction of flux passing through the aperture normalized to the total flux if the aperture were positioned to pass the entire beam, and thus have a value of 0.5 at $\psi = 0$. The measured quantities are in generally good agreement with theoretical calculations, although not as good as for the narrow aperture. This is because the narrow aperture has precisely determined edges defining a beam which entirely enters the polarimeter entrance pinhole, while for the semi-aperture the high angle limit is less well known and a smaller fraction of the wider beam actually enters the polarimeter. At 367 eV (Fig. 3a), the measured fractional flux falls more rapidly than that calculated. This results because radiation reflected from the ends of overfilled M3 are not within the phase space acceptance of the polarimeter. Such a loss of intensity for off-axis rays systematically effects polarimetry results, causing increased P_L and decreased P_C compared to calculations ignoring such effects. Such systematic departures of measured vs. calculated results are evident in Fig. 3a. Similar vignetting is evident at high positive ψ at 722 eV (Fig. 3b). The values of P_L and P_C in Fig. 3 at $\psi = 0$ mrad equal those measured for a wide open aperture passing the entire vertical fan. Thus radiation from different parts of the vertical fan add incoherently at the experiment, as expected, resulting in a beam with a significant degree of linear and both left and right circular components. Experimenters should be aware of the presence of these different polarization components when accepting a wide vertical aperture.

The semi-aperture data allow us to investigate and optimize a generalized figure of merit of interest in experiments utilizing circular polarization. For photon-limited measurements a figure of merit often used is $P_C \cdot I^{1/2}$, where I is the intensity in the incident beam. Here we substitute the fractional flux passing through the semi-aperture for I to investigate this figure of merit as the aperture position is varied. Measured and calculated quantities are in Figure 4, and both have the same general shape. A shallow minimum at $\psi = 0$ is predicted but does not appear to be observed experimentally. Vignetting effects mentioned above cause the measured figure of merit to fall more rapidly with ψ than predicted. The figure of merit is optimized with the semi-aperture at or just beyond $\psi = 0$. Thus experiments using left or right circular polarization are best illuminated with only roughly a factor of 2 loss in total intensity, assuming this figure of merit overrides other experimental considerations. For some experiments, a high value of P_C may be of greater value than this figure of merit, in which case a more restricted off-axis vertical aperture may be selected.

In summary, we have performed a systematic investigation of the effects of vertical apertures on bend magnet radiation polarization and intensity at 367 and 722 eV photon energies using a multilayer polarimeter. Polarimetry data using a narrow slit unambiguously determine the orbit plane, and are thus helpful in ensuring that optical elements are aligned vertically. To obtain a beam with a degree of linear polarization near 1, a narrow slit must be placed on the orbit plane. Even in this case, the degree of linear polarization is limited by the non-zero size of the slit, which necessarily accepts some small amount of circularly polarized radiation. The degree of unpolarized radiation is smaller than experimental error. To obtain a beam with a high degree of circular polarization we obscured the beam from above or below, with no aperture at high angle. The merit function $P_C \cdot I^{1/2}$ is maximized with the aperture obscuring not much more than half of the beam. In general the experimental measurements agree well with theoretical predictions, and cases where systematic disagreement exists can be explained by effective aperturing effects at refocusing mirror M3. Thus, assuming a well-aligned optical system and known aperture positions relative to the orbit plane, calculations alone can provide an estimate of the polarization and intensity of beams selected by different apertures. The accuracy of this estimate depends on the knowledge of the transmission properties of the beamline optics for different off-axis rays. Users of bend-magnet radiation without careful aperturing are in danger of using beams of unknown polarization state. If precise knowledge of polarization information is required, multilayer-based devices can provide this information over at least the 50 - 900 eV range.

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Figure Captions

Figure 1. The multilayer polarimeter consists of a 2 mm entrance aperture, followed by an incident intensity monitor and a rotating multilayer polarizer reflecting into a Si diode detector. Three different multilayers were attached to the polarizer stage, which was translated to position the different optics in the beam without breaking vacuum.

Figure 2. The degree of linear (P_L) and circular (P_C) polarization as the narrow (0.037 mrad) slit is stepped across the vertical opening angle are shown for 367 eV and 722 eV photon energies in (a) and (b), respectively. Symbols are experimental values, with experimental P_C values obtained assuming zero unpolarized component. Lines are calculated theoretical values. Even with the slit at $\psi = 0$ there is a small amount of circular polarization transmitted because of the non-zero slit width.

Figure 3. The degree of linear (P_L) and circular (P_C) polarization and fractional flux as the wide semi-aperture is stepped across the vertical opening angle are shown for 367 eV and 722 eV photon energies in (a) and (b), respectively. For positive ψ values the semi-aperture obscures the beam from below, while for negative ψ values the semi-aperture obscures the beam from above. Symbols are experimental values, with experimental P_C values obtained assuming zero unpolarized component. Lines are calculated theoretical values. With the semi-aperture removed to transmit the entire beam, measured P_L and P_C values equal those measured with the aperture edge at $\psi = 0$.

Figure 4. The figure of merit given by the square root of the flux fraction times the degree of circular polarization as the semi-aperture is stepped across the vertical opening angle at 366 and 722 eV. Symbols are experimental values. Lines are calculated theoretical values. The figure of merit is optimized with the semi-aperture blocking roughly half of the total intensity.

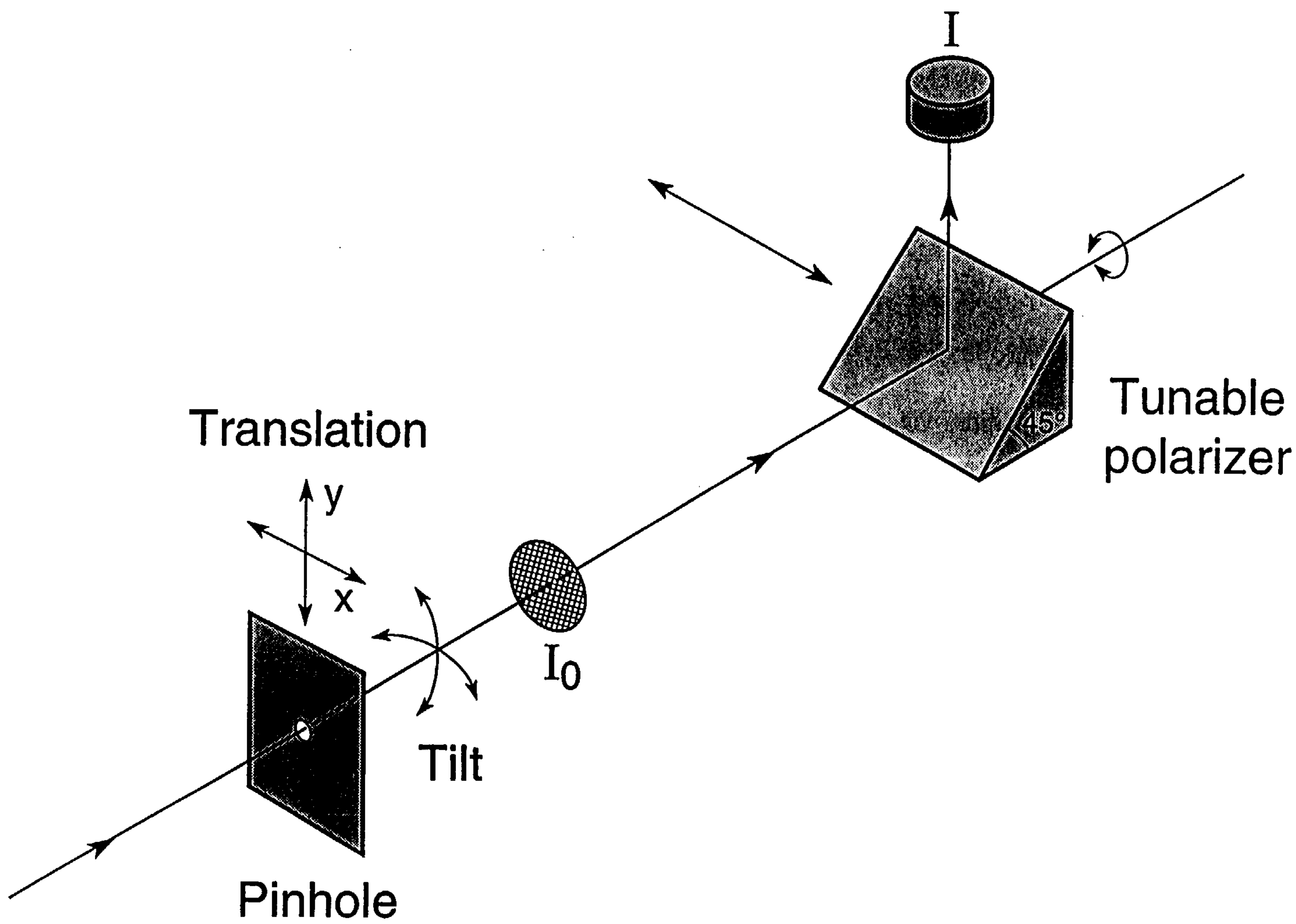

Figure 1

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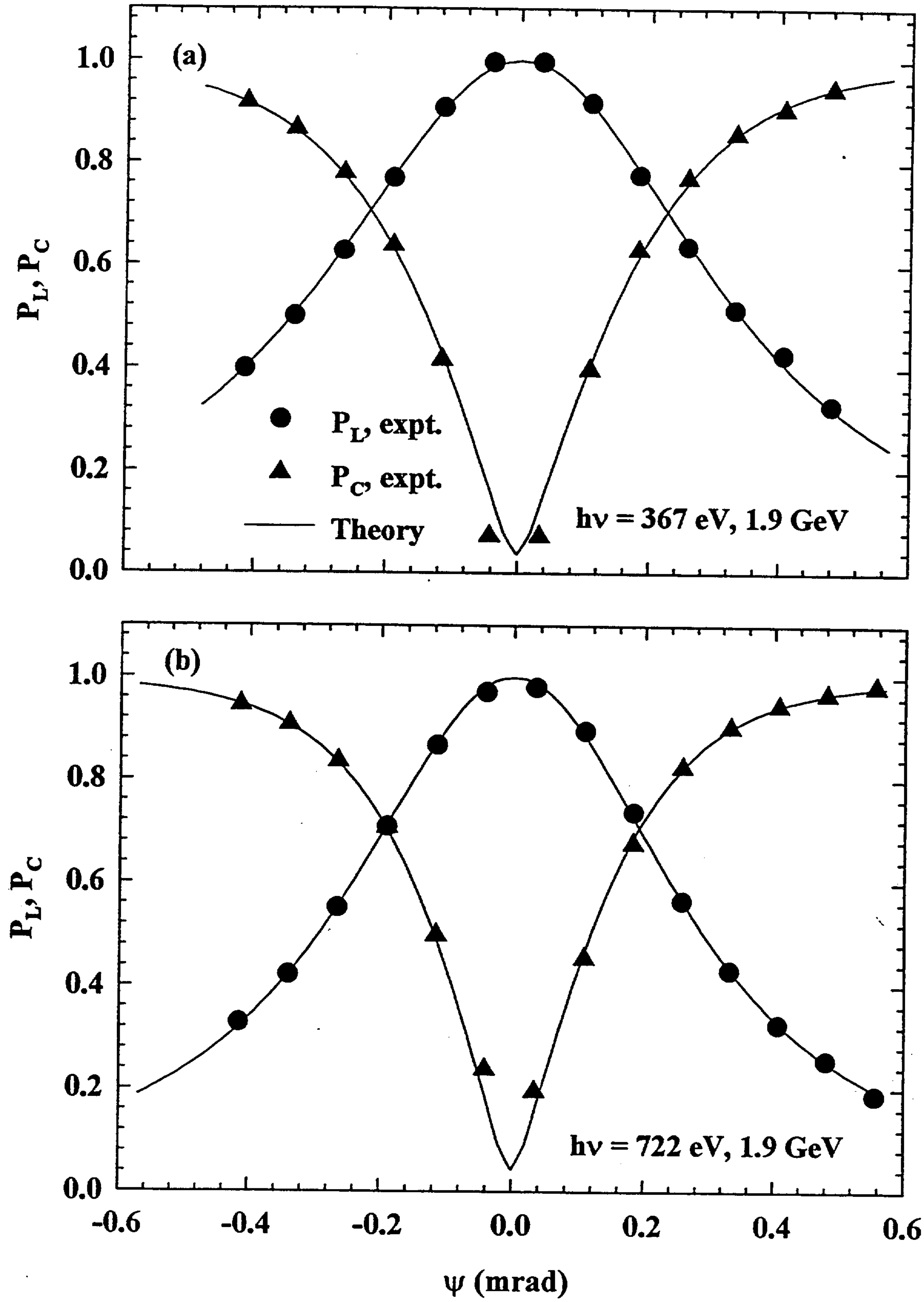
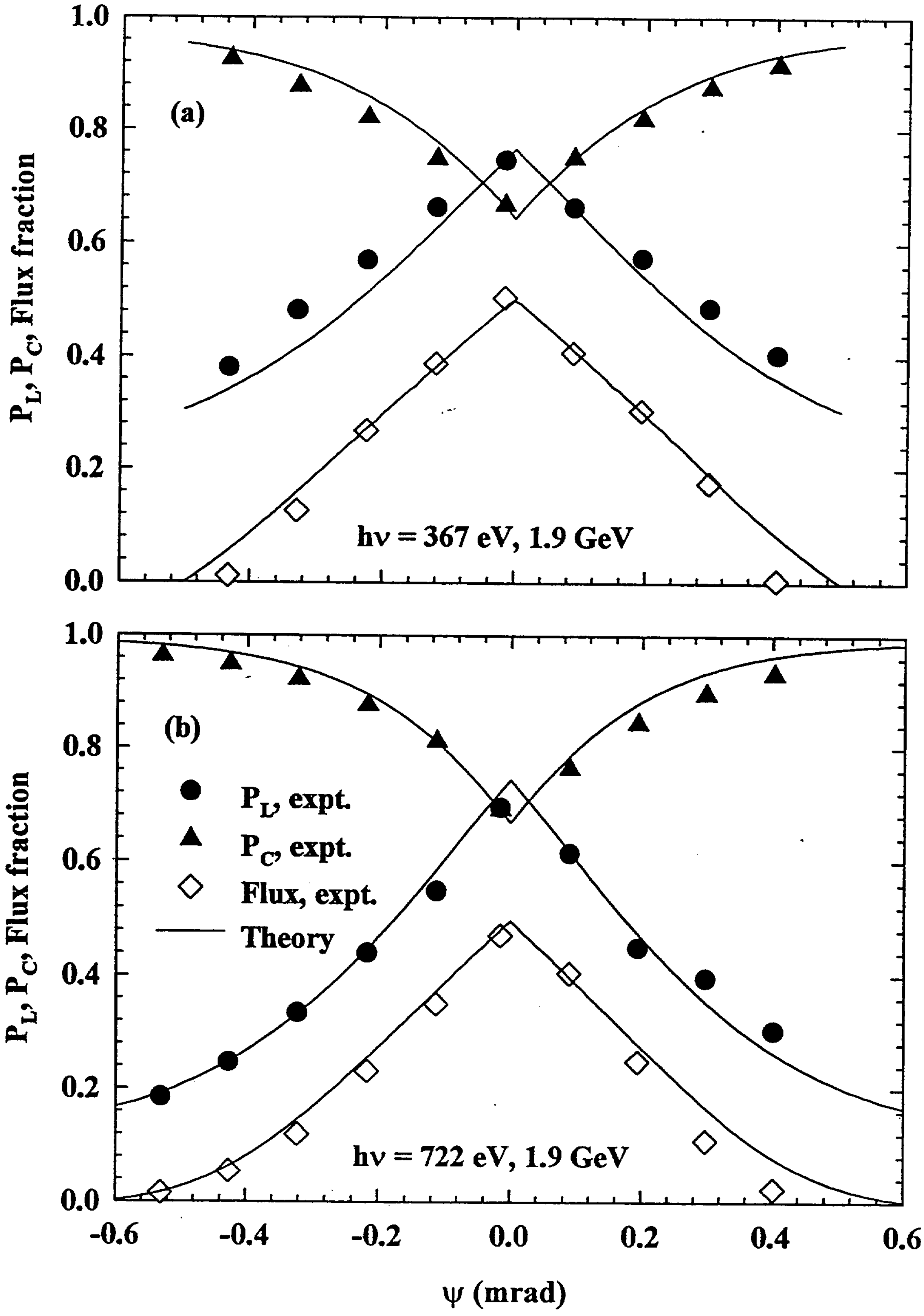
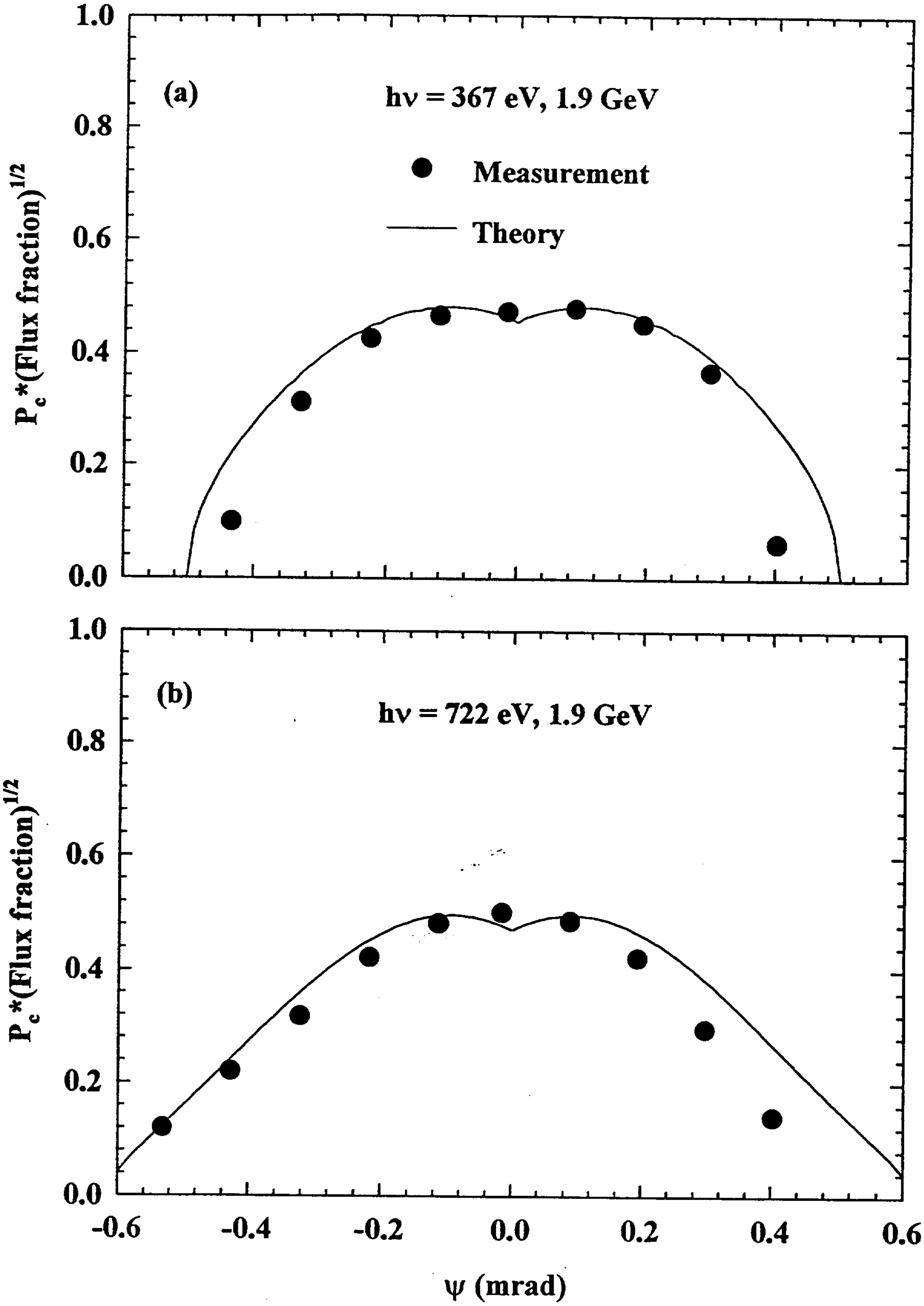

(a)
1.0
0.8
0.6
0.4
0.2
0.0
P_L, P_C
P_L, expt.
P_C, expt.
Theory
hν = 367 eV, 1.9 GeV
(b)
hν = 722 eV, 1.9 GeV
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
ψ (mrad)

Figure 2



1.0
0.8
0.6
0.4
0.2
0.0
(a)
hν = 367 eV, 1.9 GeV
(b)
P_L, expt.
P_C, expt.
Flux, expt.
Theory
hν = 722 eV, 1.9 GeV
P_L, P_C, Flux fraction
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
ψ (mrad)

Figure 3



(a)
hν = 367 eV, 1.9 GeV
Measurement
Theory
(b)
hν = 722 eV, 1.9 GeV
P_c *(Flux fraction)^1/2
1.0
0.8
0.6
0.4
0.2
0.0
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
ψ (mrad)

Figure 4