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Development of an (X, eX) spectrometer for measuring the energies of the scattered photon and recoil electron

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The design and performance of a new spectrometer for coincidence measurements between the Compton scattered photon and the recoil electron are described. Coincidence measurements give direct information on the three-dimensional electron momentum density (EMD) of condensed matter. The present spectrometer measures energy spectra of both the photon and the electron. The energy spectrum of electrons is measured by a time-of-flight method using single-bunch operation at the Photon Factory Accumulator Ring (PF-AR). The energy resolution obtained for the recoil electron is 190 eV, which is better than that of the photon detector, so that a momentum resolution of the three-dimensional EMD of 0.3 atomic units can be achieved.

Keywords: Compton scattering; coincident technique; time of flight; single bunch.

1. Introduction

The coincidence measurement between the Compton scattered photon and the recoil electron (X, eX) provides direct information on the three-dimensional electron momentum density (EMD). The feasibility of such measurements by detecting the directions of the Compton scattered photon and the recoil electron, and the energy of the photon has been reported by several authors (Rollason *et al.*, 1989; Bell *et al.*, 1990; Tschentscher *et al.*, 1993; Kurp *et al.*, 1996). The momentum space resolution obtained is limited by the energy resolution of the photon detector and it is difficult to obtain a momentum resolution better than 0.5 a.u. (atomic units). The energy width of the EMD for free and/or valence electrons in condensed matter is about 1 a.u. Therefore, it is necessary to obtain a much better momentum space resolution in order to study Fermiology and/or electron-binding energies. We have developed a new spectrometer which enables us to measure not only the above three components, *i.e.* the directions of the Compton scattered photon and the recoil electron, and the energy of the photon, but also the energy of the recoil electron by means of a time-of-flight method (TOF). The TOF measurement has given us the energy spectrum of the recoil electron with an energy resolution better than that of a photon detector, allowing us to determine the three-dimensional EMD for graphite with a momentum resolution of 0.3 a.u.

2. Kinetics

Fig. 1 shows a diagram of the Compton scattering process. An incident photon with the four-component vector $\mathbf{k}_1 = (\boldsymbol{k}_1, i\omega_1)$ makes an inelastic collision with an electron $\mathbf{p}_1 = (\boldsymbol{p}_1, iE_1)$. The photon is scattered to angle θ with $\mathbf{k}_2 = (\boldsymbol{k}_2, i\omega_2)$ and the electron is recoiled with $\mathbf{p}_2 = (\boldsymbol{p}_2, iE_2)$. In an impulse approximation, the fourfold cross section is given by equation (1) using natural units (*i.e.* $\hbar = m = c = 1$) (Rollason *et al.*, 1989)

$$\sigma = (\alpha^2/2) \int d^3\boldsymbol{k}_2 d^3\boldsymbol{p}_2 d^3\boldsymbol{p}_1 [X(R, R')/(E_2 E_1 \omega_2 \omega_1)] \times \rho(\boldsymbol{p}_1)\delta^4(\mathbf{p}_1 + \mathbf{k}_1 - \mathbf{p}_2 - \mathbf{k}_2) \quad (1)$$

where α is the fine-structure constant and X is the cross-section function as shown in (2)

$$\begin{aligned} X &= (R/R') + (R'/R) - \sin^2\theta \\ R &= -\mathbf{p}_1 \cdot \mathbf{k}_1 = -\mathbf{p}_2 \cdot \mathbf{k}_2 \\ R' &= -\mathbf{p}_1 \cdot \mathbf{k}_2 = -\mathbf{p}_2 \cdot \mathbf{k}_1. \end{aligned} \quad (2)$$

In the coincidence measurement case, the cross section is proportional to the electron momentum density itself

$$\begin{aligned} [(d^3\sigma)/(d\omega_2 d\Omega_{k_2} d\Omega_{p_2})] &= (\alpha^2/2)(\omega_2/\omega_1)(\boldsymbol{p}_2/E_1) X \rho(\boldsymbol{p}_1) \\ \boldsymbol{p}_1 &= \boldsymbol{k}_2 - \boldsymbol{k}_1 + \boldsymbol{p}_2. \end{aligned} \quad (3)$$

For coincidence events, we have the following energy conservation law

$$\hbar\omega_1 = \hbar\omega_2 + T + E_b \quad (4)$$

where T is the recoil electron energy and E_b is the electron-bonding energy. The high-resolution measurement of T gives us $\rho(\boldsymbol{p}_1)$ at high momentum resolution *via* the combination of equations (3) and (4).

3. Design of the spectrometer

Fig. 2 shows the plan and side views of the spectrometer. The incident X-rays with energy $\hbar\omega = 65$ keV impinge on the sample, which is placed at the centre of a sample chamber. The chamber is evacuated by turbo-molecular pumps and its inside is covered by permalloy to avoid the effect of magnetic fields. Samples are placed on a translation stage in order to adjust the position. Recoil electrons are detected by a multi-channel-plate (MCP) electron detector (Hamamatsu F2223-21SX) which is placed at a distance of $L = 2.00$ m from the sample under an angle of $\varphi = 12.5°$. The diameter of the MCP is 27 mm. The kinetic energy T of the recoil electron is determined by the time of flight t, as $T = (L/t)^2/2m$. The energy resolution $\Delta T/T$ is equal to $2\Delta t/t$ where Δt is the overall

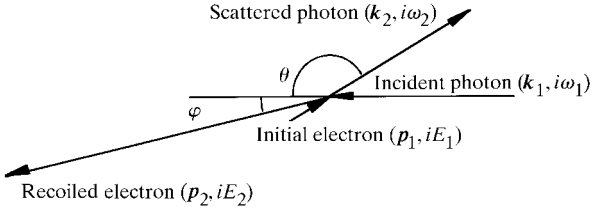

Figure 1
Momentum diagram of the Compton scattering processes.

time resolution determined by both the intrinsic bunch width of the synchrotron radiation and the time resolution of the electronics. A PIN diode with thickness 200 μm is placed upstream of the sample and serves as a timing trigger. Compton scattered photons are detected by a segmented Ge solid-state detector (SSD) that covers a scattering angle θ = 148–154°. The diameter of each element is 8 mm and the space between them is 14 mm. According to equation (3), the different scattering angles of the SSD $\boldsymbol{k}_2$ provide us with different three-dimensional EMDs with a corresponding lateral momentum p_y simultaneously. The SSD elements are placed at $p_y = -0.81, -0.36, 0.09, 0.55, 1.10$ a.u. corresponding to *a*, *b*, *c*, *d*, *e* in Fig. 2 (top right). In order to measure three-dimensional EMDs for $p_y > 1.0$, the chamber is designed to be rotated around a pivot in its centre. The resolution of p_y is 0.5 a.u. and is defined by the solid angles accepted by the photon and electron detectors.

Fig. 3 shows the electronic circuit of the spectrometer. All signals from the SSD and the MCP are collected by the multiparameter analyser (FAST/Comtech MPA-Win) in a list mode. We can obtain two kinds of coincidence data: the so-called electron branch (photon branch) which represents a measurement of the energy spectrum of recoil electrons (scattered photons) in coincidence with scattered photons (recoil electrons). We use eight inputs of the MPA in order to measure simultaneously seven outputs of the segmented SSDs that are placed at different scattering angles.

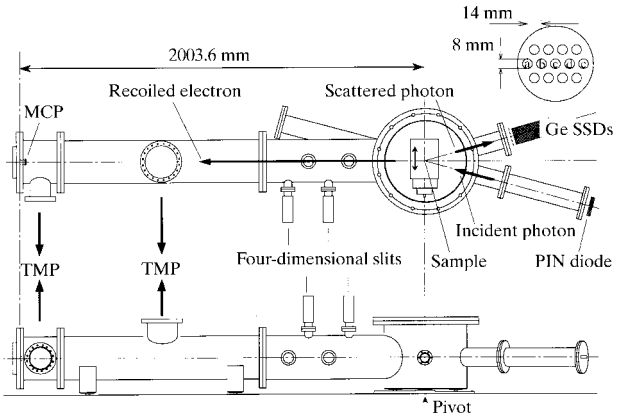

Figure 2
A side and plan view of the spectrometer and the arrangement of the SSD elements.

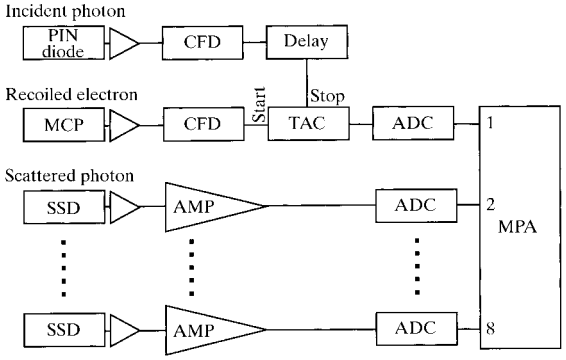

Figure 3
A block diagram of the electronic circuit of the (X, eX) spectrometer.

4. Performance (results and discussion)

The spectrometer was installed at the Photon Factory Accumulator Ring (PF-AR) NE1 beamline (KEK). The PF-AR, whose energy and stored current were 6.5 GeV and 40 mA, respectively, was operated in single-bunch mode. The time interval between two pulses was 1.28 μs. The white X-rays from an elliptical multipole wiggler, which was installed in the NE1 beamline, were monochromated by a doubly bent crystal monochromator (Kawata *et al.*, 1998). The energy of the monochromated X-rays was chosen to be 65 keV with an energy resolution $\Delta E/E \simeq 10^{-3}$. The beam size at the sample was about 0.5 mm (vertical) × 3 mm (horizontal). The sample was a graphite foil with a thickness of 20 nm. The count rate of the MCP (SSD) from the graphite foil was about 15 counts s^{-1} (50 counts s^{-1} per element). A coincidence gate time of 1.6 μs was used and the coincidence count rate was approximately 3 counts min^{-1}. This yielded a signal-to-noise ratio of 60.

Figs. 4(*a*) and 4(*b*) show TOF spectra for the non-coincidence and the coincidence measurements, respectively. There are three peaks in Fig. 4(*a*). These are located at 6.7, 14.5 and ∼32 ns and correspond to scattered photons, photoelectrons (65 keV) and recoil electrons (∼12.5 keV). The peak of the recoil electrons corresponds to the double-integrated EMD. Thus, it has a long tail caused by core-electron contributions. The full width at half-maximum (FWHM) of the photon peak (230 ps) corresponds to the overall time resolution of the system. The main contribution to the peak width is the bunch length of 200 ps. Then, the energy resolution for the recoil electrons caused by the above time resolution is 190 eV, corresponding to 0.30 a.u. momentum resolution along p_z. In the coincidence measurement, Fig. 4(*b*), there is only the recoil electron peak and the profile gives us direct information about the three-dimensional EMD. Similarly, Figs.

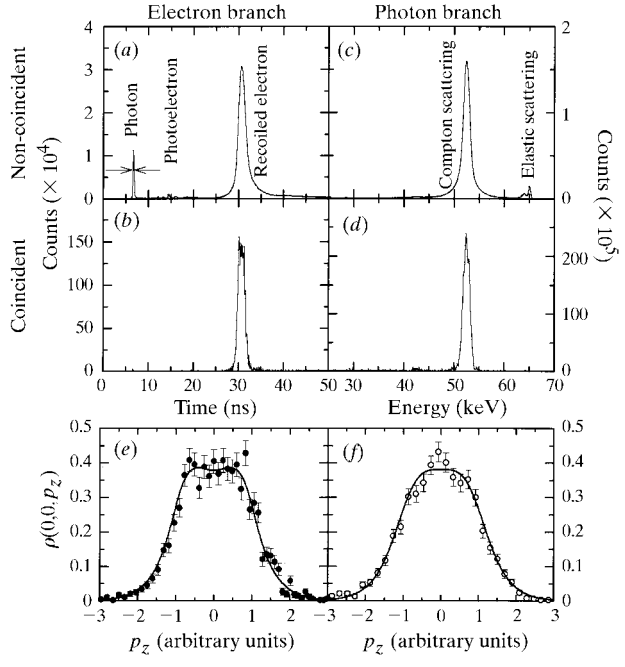

Figure 4
Experimental results of non-coincidence and coincidence measurements. Each spectrum shows the TOF profile of an electron in (*a*) non-coincidence and (*b*) coincidence cases and likewise the energy profile of a photon in (*c*) non-coincidence and (*d*) coincidence cases. (*e*) and (*f*) show the three-dimensional EMDs obtained in the electron and photon branches, respectively.

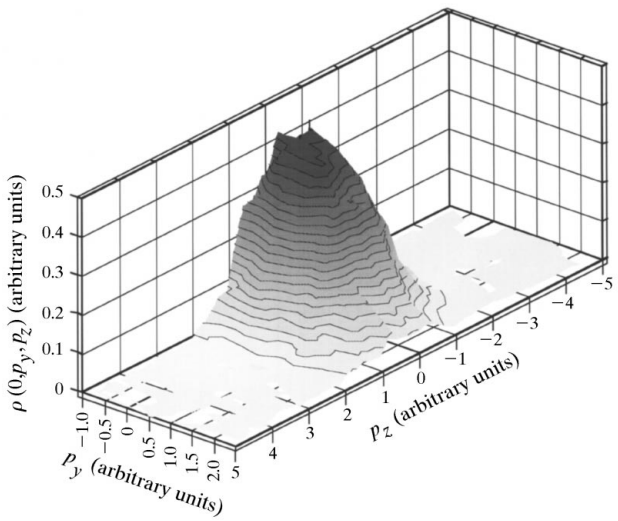

Figure 5
The electron momentum density of graphite: $\rho(0, p_y, p_z)$.

4(*c*) and 4(*d*) show energy spectra of the scattered photons in the non-coincidence and coincidence measurements, respectively. The peak in Fig. 4(*d*) corresponds to the three-dimensional EMD in the photon branch. The energy resolution of the SSD is 480 eV at 65 keV which corresponds to 0.70 a.u. momentum resolution along p_z. Figs. 4(*e*) and 4(*f*) show the three-dimensional EMDs for graphite derived from the electron and photon branches. The three-dimensional EMD in the electron branch looks like a flat top, but that in the photon branch looks like a Gaussian peak. This discrepancy is due to the difference in resolution (0.3 and 0.7 a.u.). The solid lines in Figs. 4(*e*) and 4(*f*) represent theoretical calculations of the three-dimensional EMD given by Kheifets & Vos (1995) and convoluted with the respective resolutions. The agreement with the experimental data is very good.

Fig. 5 shows the results of $\rho(0, p_y, p_z)$ for graphite by using an array of photon detectors. The three-dimensional EMDs for different p_y (−0.9–2.2 a.u.) were obtained from two data sets of φ = 12.5 and 16.8°. In this way, the three-dimensional EMD of a graphite foil could be measured with Δp_z = 0.3 a.u. and Δp_y = 0.5 a.u. resolutions in momentum space.

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