

Chapter 2

Basic Principle of Photoemission Spectroscopy and Spin Detector

To understand and discuss the experimentally obtained photoemission data, it is important to understand the principle of an experimental method and an analysis of the data. In this chapter, the basic principle of photoemission spectroscopy and the spin detector is explained, by particularly emphasizing the angle-resolved photoemission spectroscopy technique and the Mott detector.

2.1 Photoemission Spectroscopy

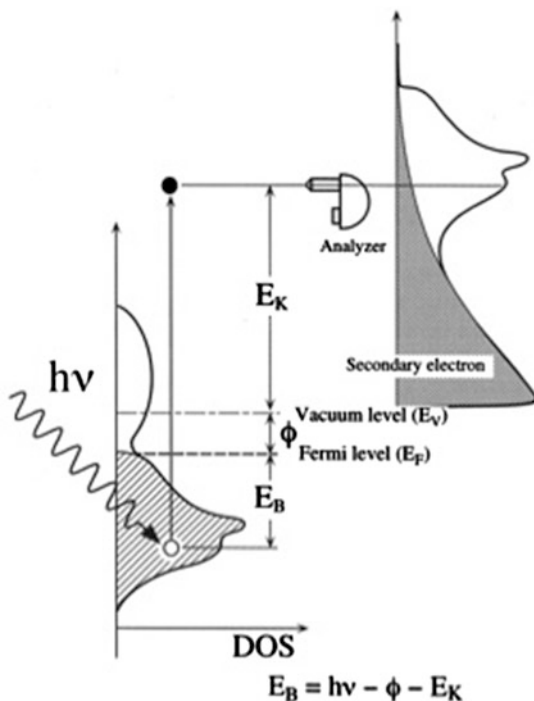
2.1.1 Principle of Photoemission Spectroscopy

Photoemission spectroscopy (PES) is a well-known technique which measures the electronic structure of a solid through the external photoelectric effect. With the types of the photon energies used for the PES measurements, the PES technique is roughly classified into two types; *i.e.*, X-ray PES (XPS) and ultraviolet PES (UPS). Recently, with the development of highly brilliant photon source in synchrotron radiation, the distinction between the XPS and UPS became unclear, thus they are rather identified by the energy region of interest, *i.e.* the core level or the valence band [1]. The PES technique is also classified into two categories; angle-integrated and angle-resolved mode. The former obtains the density of states and the later obtains the band dispersion [2]. For the PES measurement, photons excite electrons from the crystal surface by the external photoelectric effect. By fixing the energy of incident photons and observing the velocity (kinetic energy) of excited photoelectrons, it is possible to determine the density of states at a fixed binding energy of electrons in the material [1].

The principle of the PES technique is shown in Fig. 2.1. The electron is initially excited by absorbing a photon, in which energy conservation across the excitation is satisfied. From the observed photoelectron kinetic energy E_k ,

$$E_B = h\nu - E_k - \phi \quad (2.1)$$

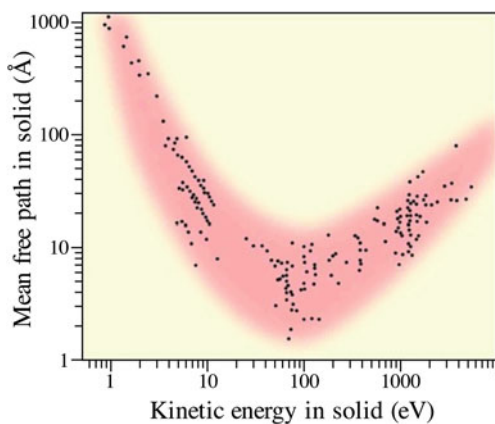
Fig. 2.1 Band structure of the sample is imaged by the excitation of electrons from the occupied states in the sample (*left*) with the photons of energy $h\nu$



where E_B is the binding energy of an electron, $h\nu$ is the incident photon energy and ϕ is the work function. Since $h\nu$ and ϕ are already-known value, we can determine E_B when E_K is identified experimentally.

The PES technique is inherently surface sensitive. Figure 2.2 shows a relationship between the escape depth and the kinetic energy of photoelectrons, called “universal curve” [3, 4]. Photoelectron escape depth varies according to the energy

Fig. 2.2 Escape depth of electrons as a function of electron kinetic energy in a solid [4]



of the photoelectrons, while it also depends on the dielectric function of the material. The escape depth of photoelectrons for the kinetic energy of 20–100 eV is only 5–10 Å. Therefore, a special attention is necessary for the surface condition of the sample.

2.1.2 Angle-Resolved Photoemission Spectroscopy

Angle-Resolved Photoemission Spectroscopy (ARPES) is a powerful and unique experimental technique to observe simultaneously energy and momentum, namely, the band dispersions. During the photoemission process, we consider the changes to the photoelectron's momentum (Fig. 2.3). In the ARPES, an initial momentum k is given by the emission polar angle θ (measured from the surface normal). The momentum of excited photoelectron in a crystal is expressed as the surface parallel component $\hbar k_{\parallel}$ and the perpendicular component $\hbar k_{\perp}$. After photoelectron is emitted from the crystal to a vacuum, the momentum is expressed as the parallel $\hbar K_{\parallel}$ and the perpendicular $\hbar K_{\perp}$ component, respectively. The momentum of exiting electrons from a sample is altered by the crystal potential at the surface. However the parallel component $\hbar k_{\parallel}$ is conserved owing to the translation symmetry of the crystal surface.

$$\hbar k_{\parallel} = \hbar K_{\parallel} \quad (2.2)$$

On the other hand, the energy of photoelectron emitted to a vacuum is given by

$$E_k = \frac{(\hbar K)^2}{2m} \quad (2.3)$$

where m is a electron mass. From Eqs. (2.1), (2.2), (2.3),

$$k_{\parallel} = \frac{\sqrt{2m(hv - \phi - E_B)}}{\hbar} \sin \theta \quad (2.4)$$

When final state of electron is assumed as free electron, the perpendicular component $k_{\perp}$ is expressed by Eq. (2.5), while it is not conserved.

$$k_{\perp} = \frac{\sqrt{2m(hv - \phi - E_B) \cos^2 \theta + U_0}}{\hbar} \quad (2.5)$$

where U_0 is variable called “inner potential”, typically it is defined as an energy of valence band bottom [5]. However, the $k_{\perp}$ value has a finite width ($\Delta k_{\perp}$) because the escape depth of photoelectron Δ_z is very short. Form the uncertainty principle,

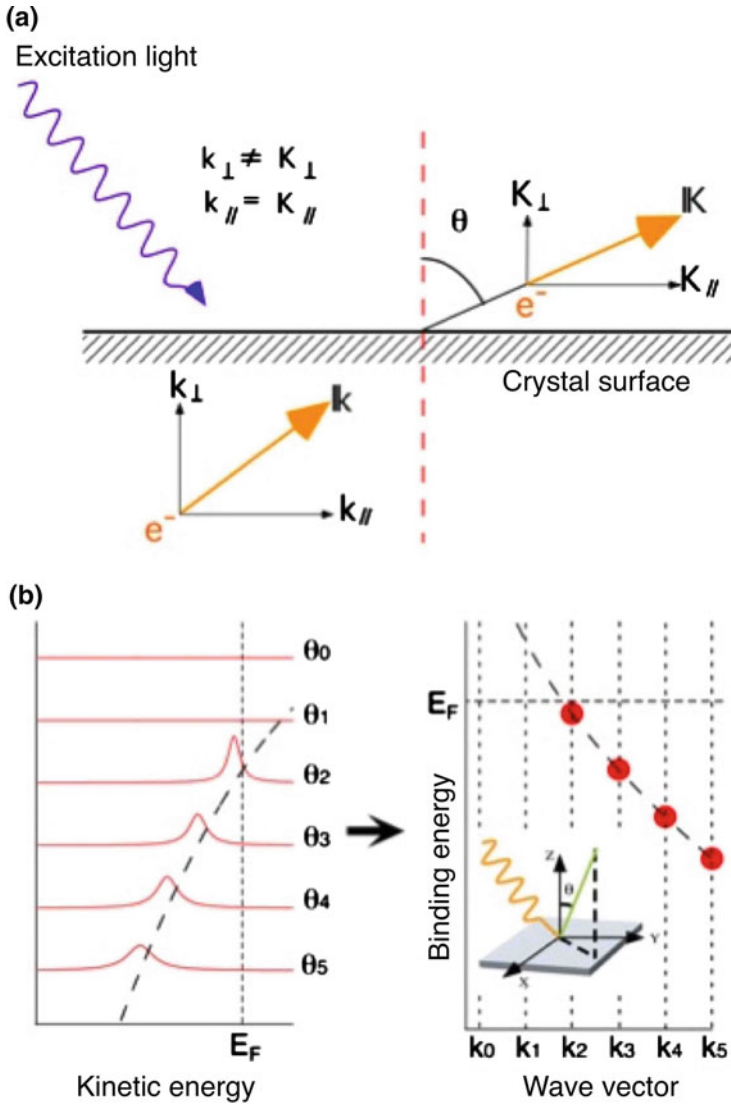


Fig. 2.3 **a** Momentum of electrons exited from the sample is altered by the crystal potential at the surface. While the parallel component ($k_{\parallel}$) is conserved by the translation symmetry of crystal, the perpendicular component is not. **b** An example of a band map. The momentum (wave vector) corresponding to the measurement angle (θ) is transformed by an Eq. (2.4)

$$\Delta_z \cdot \Delta k_{\perp} \sim 1 \quad (2.6)$$

Due to the effect which is called “final-state broadening” [6], the $K_{\perp}$ component in the final state also has a finite width.

In the case of a 2D state like the surface, the interface, and the layered materials such as graphene, it is possible to ignore $k_{\perp}$. Hence the band dispersion is simply determined experimentally from Eq. (2.4).

2.1.3 Photoemission Spectral Function

In this section, the meaning of the photoemission spectra more theoretically explained. When we do not take account into a lattice-relaxation and an electron correlation (electron-electron interaction), photoemission spectrum is expressed as the product of the initial-state (ψ_i) and final-state (ψ_f) electron wave functions. However, this picture is not completely valid where the many-body interaction exists. Photoemission spectrum is given by a spectral function which includes the many-body interaction and the final-state effect.

A photoemission or inverse photoemission spectral function at certain momentum k is given by

$$A(k, \omega) = A^+(k, \omega) + A^-(k, \omega) \quad (2.7)$$

$$A^-(k, \omega) = f(\omega)A(k, \omega) \quad (2.8)$$

$$A^+(k, \omega) = [1 - f(\omega)]A(k, \omega) \quad (2.9)$$

where $A^+(k, \omega)$ is the inverse photoemission spectral function, $A^-(k, \omega)$ is the photoemission spectral function, and $f(\omega)$ is the Fermi distribution function that represents the electron occupancy. By using the one-particle Green function $G(k, \omega)$, $A(k, \omega)$ is also given by

$$A(k, \omega) = -\frac{1}{\pi} \text{Im}G(k, \omega) \quad (2.10)$$

where

$$\begin{aligned} G(k, \omega) = & \sum_f \left| \langle \psi_f^{N-1} | c_k | \psi_i^N \rangle \right| \left[\frac{P}{\omega + E_f^{N-1} - E_i^N} - i\pi\delta(\omega + E_f^{N-1} - E_i^N) \right] \\ & + \sum_f \left| \langle \psi_f^{N+1} | c_k^+ | \psi_i^N \rangle \right| \left[\frac{P}{\omega + E_f^{N+1} - E_i^N} - i\pi\delta(\omega + E_f^{N+1} - E_i^N) \right] \end{aligned} \quad (2.11)$$

P is the Cauchy integral, ψ_i (ψ_f) and E_i (E_f) are wave function and intrinsic energy of the initial (final) state. c_k (c_k^+) is annihilation (creation) operator [6]. The former term of Eq. (2.11) corresponds to photoemission spectroscopy, and the later is to inverse photoemission spectroscopy. Thus, $A(k, \omega)$ is given by

$$\begin{aligned}
A(k, \omega) = & \sum_f \left| \left\langle \psi_f^{N-1} \right| c_k \left| \psi_i^N \right\rangle \right| \delta(\omega + E_f^{N-1} - E_i^N) \\
& + \sum_f \left| \left\langle \psi_f^{N+1} \right| c_k^\dagger \left| \psi_i^N \right\rangle \right| \delta(\omega + E_f^{N+1} - E_i^N)
\end{aligned} \quad (2.12)$$

The former term of Eq. (2.12) corresponds to the photoemission spectral function, and the to the inverse photoemission spectral function. In the one-electron approximation without interaction, $G(k, \omega)$ and $A(k, \omega)$ is given by

$$G(k, \omega) = \frac{1}{\omega - \varepsilon_k^0 + i0^+} \quad (2.13)$$

$$A(k, \omega) = \delta(\omega - \varepsilon_k^0) \quad (2.14)$$

where ε_k^0 is the binding energy of the bare band.

Now we consider a case with interaction. Then $G(k, \omega)$ and $A(k, \omega)$ are given with the use of self-energy $\Sigma(k, \omega)$ by,

$$G(k, \omega) = \frac{1}{\omega - \varepsilon_k^0 - \Sigma(k, \omega)} \quad (2.15)$$

$$A(k, \omega) = \frac{1}{\pi} \frac{-\text{Im}\Sigma(k, \omega)}{[\omega - \varepsilon_k^0 - \text{Re}\Sigma(k, \omega)]^2 + [\text{Im}\Sigma(k, \omega)]^2} \quad (2.16)$$

Equation (2.15) is called the Dyson equation. $\text{Re}\Sigma$ and $\text{Im}\Sigma$ satisfy the following conditions from the Kramers-Kronig relation.

$$\text{Re}\Sigma(k, \omega) - \text{Re}\Sigma(k, \mu) = \frac{1}{\pi} \text{P} \int_{-\infty}^{\infty} \frac{\text{Im}\Sigma(k, \omega') - \text{Im}\Sigma(k, \infty)}{\omega - \omega'} d\omega' \quad (2.17)$$

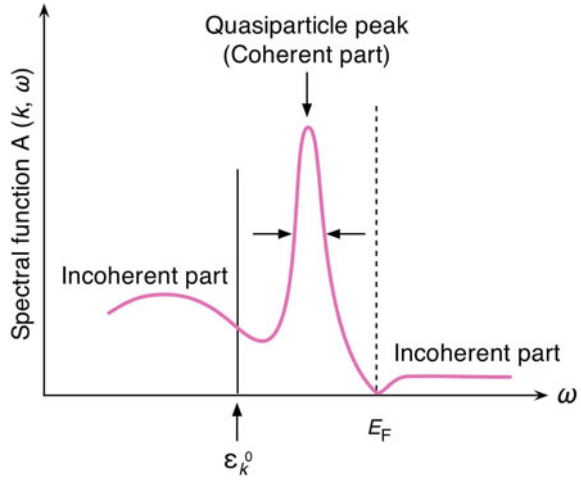
$$\text{Im}\Sigma(k, \omega) - \text{Im}\Sigma(k, \infty) = -\frac{1}{\pi} \text{P} \int_{-\infty}^{\infty} \frac{\text{Re}\Sigma(k, \omega') - \text{Re}\Sigma(k, \mu)}{\omega - \omega'} d\omega' \quad (2.18)$$

$\text{Re}\Sigma$ and $\text{Im}\Sigma$ can be calculated when we know $G(k, \omega)$.

$$\text{Im}\Sigma(k, \omega) = \frac{\text{Im}G(k, \omega)}{\text{Re}G(k, \omega)^2 + \text{Im}G(k, \omega)^2} \quad (2.19)$$

$$\text{Re}\Sigma(k, \omega) = \omega - \varepsilon_k^0 - \frac{\text{Re}G(k, \omega)}{\text{Re}G(k, \omega)^2 + \text{Im}G(k, \omega)^2} \quad (2.20)$$

Fig. 2.4 An example of a photoemission spectral function in a system with the strong many-body interactions [6]



From these equations, we enable to calculate self energy if we know the spectral function.

Lifetime of a quasi-particle is proportional to $|\text{Im}\Sigma(k, \omega)|^{-1}$, and a peak width of the quasi-particle is $2|\text{Im}\Sigma(k, \omega)|$. $\text{Re}\Sigma(k, \omega)$ corresponds to an energy shift from ϵ_k^0 , reflecting the interaction. A quasiparticle peak (coherent part) arises as a sharp peak, while broad incoherent part arises in an unoccupied state and in the higher E_B side than ϵ_k^0 (Fig. 2.4) [6].

2.1.4 Photoemission Spectral Intensity

The photoemission spectral intensity observed in the experiment is given by

$$I(k, \omega) = I_0(k) \sum_{\delta k} d\omega' A(k', \omega') f(\omega') R(\omega, \omega') + SOL + Background \quad (2.21)$$

where

$$I_0(k) \propto |\langle \psi_f | A \cdot p | \psi_i \rangle|^2 \quad (2.22)$$

The I_0 depends on the polarization vector of incident light (A) and the momentum vector (p), and the atomic orbital component. The R , which is the resolution function of the spectrometer, is the Gaussian. The *SOL* (second order light) is a background by an incident light and the *Background* includes other effects such as secondary electrons.

From Eq. (2.22), it is expected that $I_0(k)$ has a maximum value when the broadening of the initial state $\Delta\psi_i$ is close to de Broglie wave length of the final

state ψ_f . Namely, there is a most effective energy of the incident light to excite an electron in a specific orbital. The photo-excitation cross-section can be calculated for the respective atomic orbital [7]. In general, electrons in the s - or p -orbital show high cross-section with low-energy photons, while the d - or f -electrons show the same with high-energy photons.

2.1.5 Energy Distribution Curve and Momentum Distribution Curve

In the ARPES measurements, as displayed in Fig. 2.5, the spectra measured at a constant k is called the energy distribution curve (EDC) and the spectra measured at a constant energy is called the momentum distribution curve (MDC). Photoemission spectrum is usually referred to the EDC. The EDC is more suitable to show the “light” band dispersion, while the MDC is more effective for the “heavy” band. Peaks in the EDCs or the MDCs correspond to the high photoelectron density, indicating the center of an electron band. Other information, such as a quasiparticle lifetime, can be extracted by observing the width of these peaks [8].

2.2 Spin Detector

2.2.1 Various Spin Detectors

The nature of electrons in solids is described by three quantum parameters, energy, momentum, and spin. The first experiment which observed the electron spin was reported by Stern and Gerlach in 1922 [9]. Figure 2.6 is a schematic view of this experiment. A silver (Ag) atom is heated and vaporized in an oven, and then it becomes atomic beam and is evaporated to a photographic plate through a slit. In this experiment, atomic beam of Ag passes and split by gradient magnetic field applied from a slit to a photographic plate. From this result, Uhlenbeck and Goudsmit proposed that an electron has angular momentum corresponding to “spin” and magnetic momentum [10]. Now we commonly understood that such a phenomenon is caused by the Ag $5s$ electron spin. However, it is unrealistic to observe electron spin by this method because electron is much lighter than Ag atom and the resultant split size is expected to be fairly small.

For the electron spin-polarization measurements, many kinds of spin detector have been developed utilizing various spin-dependent scattering processes as shown in Table 2.1 [11–15]. Common characteristics of these detectors are to use heavy elements as a target like gold (Au) and tungsten (W) owing to their large spin-orbit coupling (SOC). Recently, spin detector which utilizes the spin exchange interaction has been also developed [14]. Among them, the Mott detector is one of

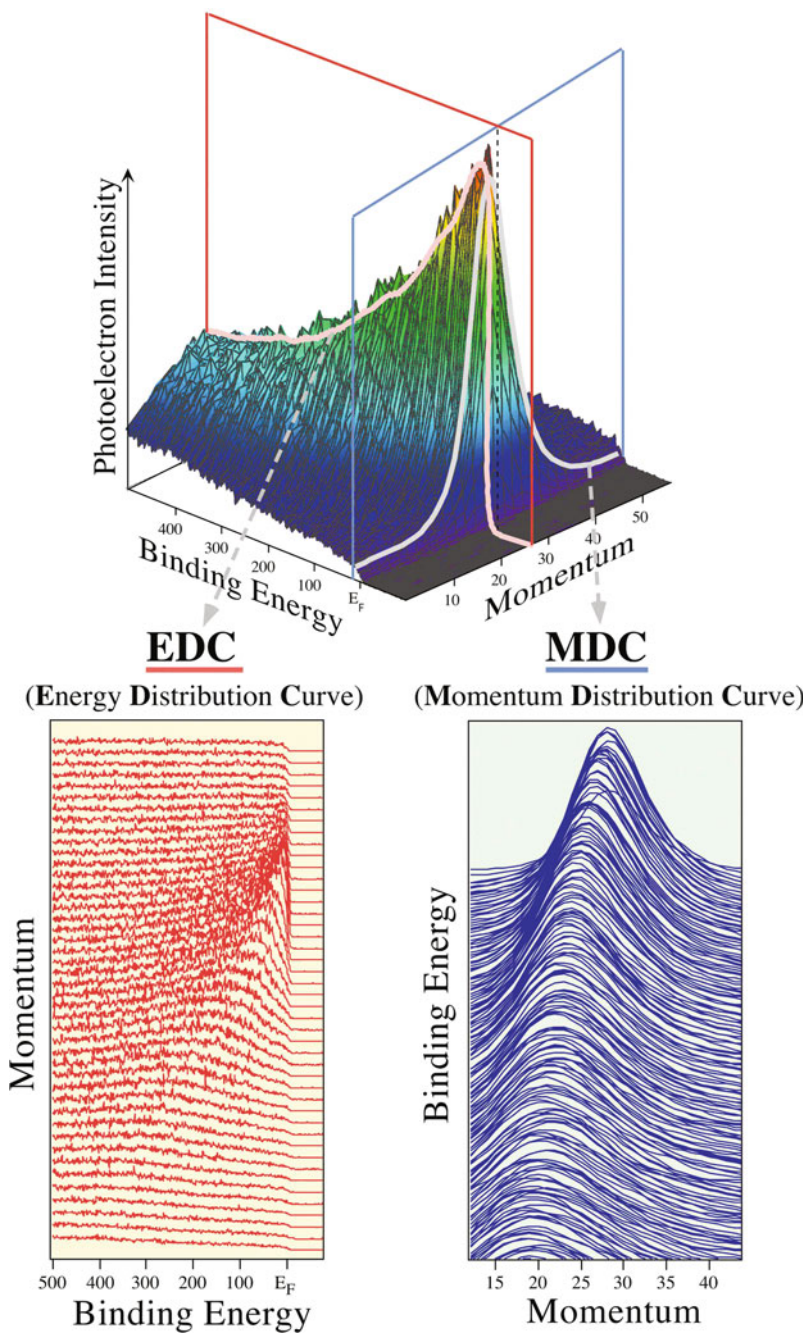


Fig. 2.5 Comparison between EDC and MDC

Fig. 2.6 Schematic view of Stern-Gerlach experiment

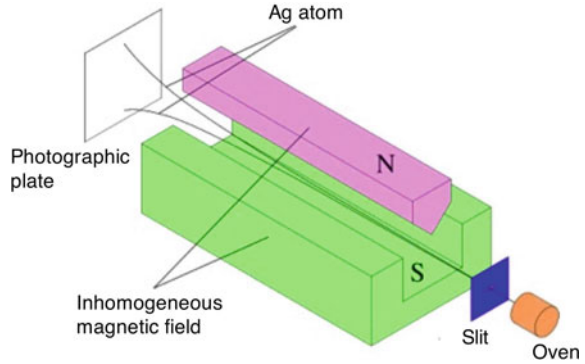


Table 2.1 Comparison of the performance of various spin detectors [15]

Method	Interaction	Operation voltage	S_{eff}	Figure of merit	Target
Mott	Spin-orbit	20–100 kV	0.1–0.2	$1\text{--}5 \times 10^{-4}$	Au thin film
SPLEED	Spin-orbit	150 V	0.2–0.3	$1\text{--}2 \times 10^{-4}$	W single crystal
Diffuse scattering	Spin-orbit	150 V	~ 0.2	$\sim 1 \times 10^{-4}$	Au thin film
VLEED	Spin-exchange	6–10 V	0.3–0.4	$\sim 10^{-2}$	Fe single crystal

the most widely used detector to measure the electron spin polarization due to its high stability and usefulness of the self-calibration. From the next section, principle of the Mott scattering and the detail of Mott detector are explained.

2.2.2 Principle of the Mott Scattering

The asymmetry of the spin polarization in the Mott scattering arises from SOC between the electron and the nucleus. Mott spin detector is based on this scattering [16]. As seen in Fig. 2.7, in the electron's rest frame, the positively charged nucleus looks to move toward the electron and, an effective magnetic field $\mathbf{B}$ is generated at the position of the electron. The magnetic field is given by

$$\mathbf{B} = -\frac{1}{c}\mathbf{v} \times \mathbf{E} = \frac{Ze}{cr^3}\mathbf{r} \times \mathbf{v} = \frac{Ze}{mcr^3}\mathbf{L} \quad (2.23)$$

where $\mathbf{v}$ is the velocity of the electron, $\mathbf{r}$ is the distance between the electron and the nucleus, and Z is the atomic number of the nucleus. The electron orbital angular momentum about the nucleus $\mathbf{L}$ and electric field of the nucleus $\mathbf{E}$ are given by

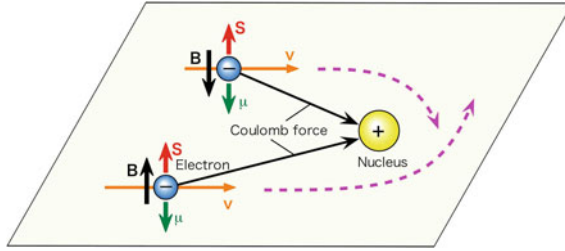


Fig. 2.7 Electron experiences electric and magnetic fields by a scattering to a nucleus (Mott scattering)

$$\mathbf{E} = (Ze/r^3)\mathbf{r} \quad (2.24)$$

$$\mathbf{L} = m\mathbf{r} \times \mathbf{v} \quad (2.25)$$

The magnetic moment of an electron μ_e is defined as

$$\mu_e = -\frac{g_s e}{2mc}\mathbf{S} \quad (2.26)$$

where g_s is the gyromagnetic ratio ($g_s \approx 2$), it means that; when an electron has upward spin perpendicular to orbital plane, μ_e points to the downward direction. Here we take into account spin precession (Thomas precession 1/2), and the potential by the SOC (V_{LS}) that arises from the interaction between the electron magnetic moment and the $\mathbf{B}$ of the nucleus, as given by

$$V_{LS} = -\mu_e \cdot \mathbf{B} = \frac{Ze^2}{2m^2c^2r^3}\mathbf{L} \cdot \mathbf{S} \quad (2.27)$$

The sign of the V_{LS} is determined by whether $\mathbf{S}$ and $\mathbf{L}$ are aligned or anti-aligned. The SOC becomes the maximum when the spin direction is perpendicular to the orbital plane. It is indicated that the upward (downward) spin is easy to be scattered toward right (left) way. In addition, V_{LS} becomes larger as the Z is larger and the $\mathbf{v}$ is faster, so that the Mott detector makes electron collide to a target prepared by heavy element such as Au at high speed (voltage).

Now we consider the system in Fig. 2.8a. The electron beam strikes toward the Au target by high voltage. Depending on the scattering angle, the differential scattering cross section $\sigma(\theta)$ also shows an asymmetry. $\sigma(\theta)$ is given by

$$\sigma(\theta) = I_0(\theta) \cdot (1 + S(\theta)\mathbf{P} \cdot \hat{\mathbf{n}}) \quad (2.28)$$

where $I_0(\theta)$ is the differential scattering cross section for unpolarized electron beam, $\mathbf{P}$ is the polarization vector of incident electrons, $\hat{\mathbf{n}}$ is the unit vector normal to a scattering plane, and $S(\theta)$ is the Sherman function. From Eq. (2.28), we notice that a vertical spin component to a scattering plane only contributes to the $\sigma(\theta)$. Scattering

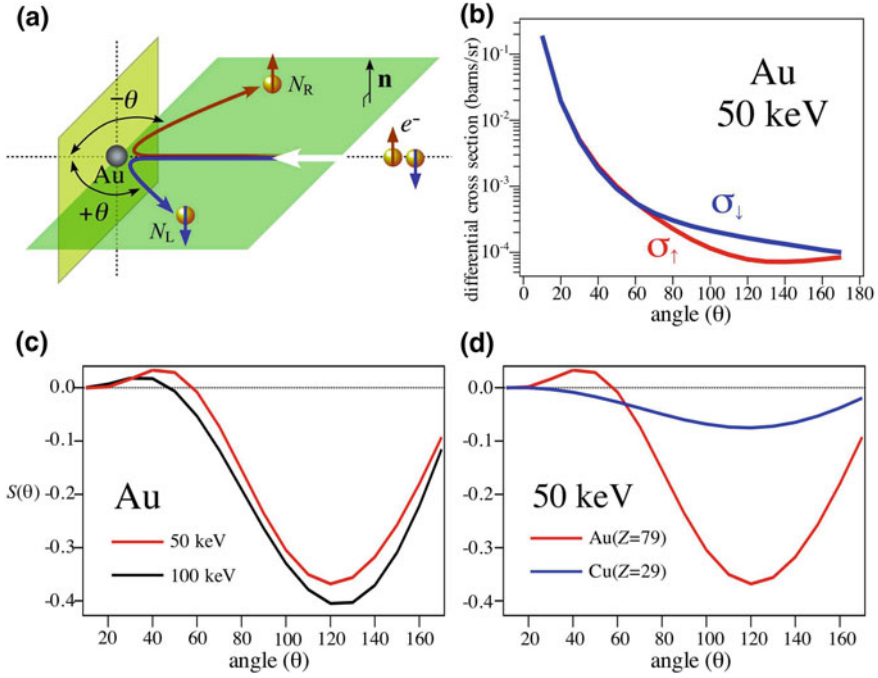


Fig. 2.8 **a** Schematic view of electron spin scattering for heavy atom. **b** Cross section for gold as a function of back scattering angle at 50 keV. **c**, **d** Energy and atomic-number dependence of the Sherman function, respectively [17]

asymmetry $A(\theta)$ is defined by the differential scattering cross section for up and down spin $\sigma_{\uparrow}(\theta)$, $\sigma_{\downarrow}(\theta)$

$$A(\theta) \equiv \frac{\sigma_{\uparrow}(\theta) - \sigma_{\downarrow}(\theta)}{\sigma_{\uparrow}(\theta) + \sigma_{\downarrow}(\theta)} = PS(\theta) \quad (2.29)$$

As shown in Fig. 2.8b, $\sigma(\theta)$ and $A(\theta)$ depend on the scattering angle and they have a maximum value at $\theta = 120^\circ$ [17]. $S(\theta)$ also becomes the maximum at $\theta = 120^\circ$, however the $S(\theta)$ value strongly depends on the incident electron energy and Z of the target material (Fig. 2.8c, d). The absolute value of $S(\theta)$ becomes larger as Z becomes larger and v becomes faster. Since the up spin is scattered toward the $-\theta$ side and the down spin toward the $+\theta$ side, we need a pair electron detectors which are set to $\pm 120^\circ$.

2.2.3 Mott Detector

A traditional Mott detector utilizes incident electron with high energy (~ 100 keV) to enhance the scattering asymmetry. One needs a special attention to suppress the discharge in high-voltage electrode for the Mott detector, thus the large-detector

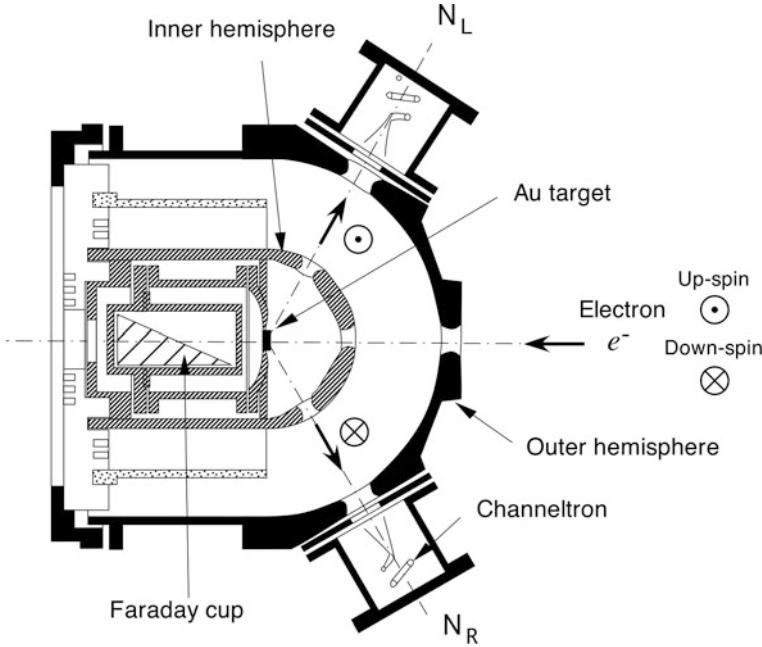


Fig. 2.9 Schematic view of mini Mott detector based on retarding-potential design

size is (over 1 m^3) a demerit. However, recently, the mini Mott detector with “retarding -potential type” has been developed; this can be operated at relatively low energy ($\sim 30 \text{ keV}$) [18]. Figure 2.9 shows a schematic view of the retarding-potential-type mini Mott detector. Now the size of the Mott detector is much smaller than the previous case. In this type of Mott detector, energy-reduced electrons by a multiple scattering are excluded by the retarding potential. A Mott detector has usually two-pair electron detectors such as channeltron in order to observe spin for two axes. Lens elements are built into the Mott detector to make a focused electron beam onto the target. Au ($Z = 79$) is widely used as a target material owing to its high stability. Recently thorium ($Z = 90$) is also used [19], while it requires scrupulous attention for handling due to its radioactive nature. Thin film target is used to reduce multiple and plural scatterings which reduce the scattering asymmetry. Taking account into the multiple scatterings, the Sherman function is replaced with an “effective Sherman function S_{eff} ”. The value of S_{eff} is specific to each instrument. The absolute value of $S_{eff}(\theta)$ is smaller than the $S(\theta)$, while the variation of $S_{eff}(\theta)$ near 120° is milder than $S(\theta)$.

The efficiency of the Mott detector is defined as

$$\varepsilon = |S_{eff}(\theta)|^2 \cdot I/I_0 \quad (2.30)$$

where ε is called as a figure of merit, I_0 is the number of electrons entering the Mott detector and I is the total number of the scattered electrons measured by the left and right electron detectors. A typical value of $S_{eff}(\theta)$ for various mini Mott detectors with the electron acceleration energy of 25 kV is ~ 0.1 [19], thus the typical figure of merit is the order of 10^{-4} . The efficiency of detecting the spin polarization is three orders-of-magnitude lower than that of the regular (non-spin-resolved) measurement. So for high efficiency, electron detectors are centered at $\pm 120^\circ$ and enables to collect electrons with a finite acceptance angle.

2.2.4 Derivation Method of Spin Polarization Spectrum

In this section an actual procedure to obtain the spin-polarized spectra from the experimentally obtained spectra is explained.

Figure 2.10 illustrates the procedure for this. When the EDC has spin polarization like Fig. 2.10a, we can obtain the “total” spectrum by spin-integrated ARPES. Here the number of up or down spins is expressed as $N_\uparrow$, $N_\downarrow$ respectively, and the “total” spectrum is given by $N_\uparrow + N_\downarrow$. As displayed in Fig. 2.10b, the spin polarization P range is $-1 \leq P \leq 1$. N_L (N_R) denotes the intensity measured in the left (right) channeltron detector at angle θ ($-\theta$). From Eq. (2.28), N_L and N_R are given by

$$N_L = N_\uparrow I_0(\theta)(1 + S_{eff}(\theta)) + N_\downarrow I_0(\theta)(1 - S_{eff}(\theta)) \quad (2.31)$$

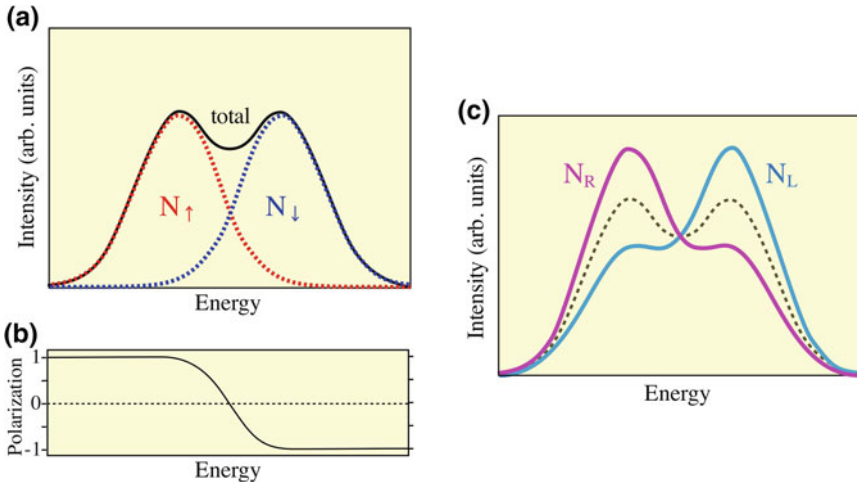


Fig. 2.10 Procedure to extract the spin-resolved spectra from the experimentally observed data. **a** $N_\uparrow$ and $N_\downarrow$ are intrinsic spin-polarized spectra. A solid line (Total) is spin-integrated photoemission spectrum. **b** Spin polarization as a function of energy in **a**. **c** Spectra for $S_{eff} = 0.3$ determined from the spin-resolved photoemission experiment

$$N_R = N_{\uparrow} I_0(\theta)(1 - S_{eff}(\theta)) + N_{\downarrow} I_0(\theta)(1 + S_{eff}(\theta)) \quad (2.32)$$

This represents the experimentally obtained spin-resolved spectra (Fig. 2.10c). Next, we calculate “ $N_L + N_R$ ” and “ $N_L - N_R$ ” using Eqs. (2.31) and (2.32).

$$N_L + N_R = 2I_0(\theta)(N_{\uparrow} + N_{\downarrow}) \quad (2.33)$$

$$N_L - N_R = 2I_0(\theta)S_{eff}(\theta)(N_{\uparrow} - N_{\downarrow}) \quad (2.34)$$

Here, P and $A(\theta)$ are defined as

$$P = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} \quad (2.35)$$

$$A(\theta) = \frac{N_L - N_R}{N_L + N_R} \quad (2.36)$$

From Eqs. (2.29), (2.35), and (2.36),

$$A(\theta) = \frac{N_L - N_R}{N_L + N_R} = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} S_{eff}(\theta) \equiv P S_{eff}(\theta) \quad (2.37)$$

Finally we deform the Eq. (2.37) to calculate $N_{\uparrow}$ and $N_{\downarrow}$.

$$\begin{aligned} 1 + P &= 1 + \frac{A(\theta)}{S_{eff}(\theta)} = \frac{2N_{\uparrow}}{N_{\uparrow} + N_{\downarrow}} \\ 1 - P &= 1 - \frac{A(\theta)}{S_{eff}(\theta)} = \frac{2N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} \end{aligned} \quad (2.38)$$

$$\begin{aligned} N_{\uparrow} &= \frac{1}{2}(1 + P)(N_{\uparrow} + N_{\downarrow}) \\ N_{\downarrow} &= \frac{1}{2}(1 - P)(N_{\uparrow} + N_{\downarrow}) \end{aligned} \quad (2.39)$$

Thus if the $S_{eff}(\theta)$ is known and the asymmetry is measured, the polarization can be calculated; therefore it is essential to determine an accurate S_{eff} value of the Mott detector prior to the experiment.

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