Ground-State Wavefunctions in Solids

PROBING *VIA* COMPTON SCATTERING

J.R. Schneider[1] and F. Bell[2]

[1] *Hamburger Synchrotronstrahlungslabor HASYLAB at the Deutsches Elektronen-Synchrotron, Hamburg, Germany*

[2] *Physics Section, Ludwig Maximilians University, Munich, Germany*

Direct determinations of electron momentum densities in solids by measuring Compton scattered photons in coincidence with recoil electrons will allow more precise testing of electronic structure calculations.

Calculating the electronic structures of solids is a major issue in modern physics. Far-reaching approximations have to be made to solve this extreme many-body problem, so calculated results need to be checked by experiment. Single-electron excitation energies are measured using angle-resolved photoemission spectroscopy, which has proved to be one of the most powerful techniques for studying the bulk and surface electronic states of solids. We aim here to demonstrate the impact of modern Compton scattering experiments, that probe ground-state wavefunctions *via* the electron momentum distribution, on understanding many-body effects in solids.

Electronic Structure Calculations

Today, most calculations of the electronic structure of solids are performed within density-functional theory by solving the Kohn-Sham single-particle equations in position space [1]:

$$\{(\hbar^2/2m)\nabla^2 + v_{eff}[\rho](\boldsymbol{r})\}\phi_i(\boldsymbol{r}) = \varepsilon_i\phi_i(\boldsymbol{r}).$$

This highly successful approach relies on the existence of a model system of N non-interacting fermions which has the same charge density $\rho(\boldsymbol{r})$ as the interacting system of interest. Then, as shown by Hohenberg and Kohn in 1964, an effective one-particle potential $v_{eff}[\rho](\boldsymbol{r})$ must exist which generates this charge density. The effective potential contains a term describing exchange and correlation $v_{xc}[\rho](\boldsymbol{r})$ that is known only approximately. The total energy of the system is calculated from the eigenvalues ε_i of the Kohn-Sham equations and the eigenfunctions $\phi_i(\boldsymbol{r})$ determine the charge density according to

$$\rho(\boldsymbol{r}) = \sum_i^{occ} |\phi_i(\boldsymbol{r})|^2$$

The eigenfunctions ϕ_i are often successfully interpreted as independent wavefunctions. However, this practice lacks rigour because they are formal variational functions which only have meaning for the electronic charge density. Hence, in calculating other ground-state operators, one should consider the effect of a correlation correction term which is added to the expectation value for the non-interacting Kohn-Sham system [2]. The significance of this term with repect to momentum densities will be demonstrated later.

Ignoring for now the correlation correction term, the momentum density $\rho(\boldsymbol{p})$ is calculated from the Fourier transforms of the eigenfunctions of the non-interacting Kohn-Sham system

$$\rho(\boldsymbol{p}) = \sum_i^{occ} |\chi_i(\boldsymbol{p})|^2,\ \chi_i(\boldsymbol{p}) = (2\pi)^{-3/2} \int \phi_i(\boldsymbol{r}) e^{i\boldsymbol{p}\cdot\boldsymbol{r}} d\boldsymbol{r}.$$

At this point, we note that charge and momentum densities provide complementary information on the electronic structure. In the framework of the independent-particle model, this is easily seen from the Fourier transform of the momentum density, which equals the autocorrelation function of the position space wavefunction $B(\boldsymbol{r})$:

$$B(\boldsymbol{r}) = \int \rho(\boldsymbol{p}) e^{i\boldsymbol{p}\cdot\boldsymbol{r}} d\boldsymbol{p} = \sum_i^{occ} \int \phi_i^*(\boldsymbol{r}) \cdot \phi_i(\boldsymbol{r}-\boldsymbol{r}')\, d\boldsymbol{r}'.$$

In a classical Compton scattering experiment one obtains information about the momentum density, *i.e.*, the diagonal terms of the single-electron momentum space density matrix. This is because the initial photon state can be represented as a propagating plane wave exciting each point in position space to an equal amount.

A more specific sampling of position space can be realized by exciting standing wave fields due to Bragg diffraction in perfect crystals, thus obtaining information about the non-diagonal terms of the matrix. The first experiments along these lines were successfully performed by Schülke *et al.* [3] in 1986 using synchrotron radiation at HASYLAB.

The electronic band structure (as obtained from photoemission experiments) and ground-state charge and momentum densities are often considered as being unrelated. They are, however, special projections of the single-particle Green function of the system. Photoemission experiments provide information on the locations of poles of the Green function, while experiments probing electron momentum densities sample the magnitude of the Green function residues. Both types of measurements are therefore needed, in principle, for a complete check of theoretical calculations.

Electronic Momentum Densities

For a general understanding of momentum densities, it is instructive to examine the difference between the crystal momentum $\boldsymbol{k}$ and the electron momentum $\boldsymbol{p}$ in the independent-particle model by applying Bloch's theorem to the electron wavefunction $\phi_k(\boldsymbol{r})$ for a given band $\phi_k(\boldsymbol{r}) = u_k(\boldsymbol{r})\exp(i\boldsymbol{k}\cdot\boldsymbol{r})$.

The periodic function $u_k(\boldsymbol{r})$ can be expanded in a Fourier series in reciprocal lattice vectors $\boldsymbol{G}$ with coefficients $A_G(\boldsymbol{k})$ and Fourier transformed to give

$$\rho(\boldsymbol{p}) = \sum_k n(\boldsymbol{k}) \cdot \sum_G |A_G(\boldsymbol{k})|^2 \,.\, \delta(\boldsymbol{p}-\boldsymbol{k}-\boldsymbol{G})$$

for the momentum density, where the occupation number $n(\boldsymbol{k})$ is equal to unity for occupied and zero for unoccupied $\boldsymbol{k}$ states inside the central Brioullin zone. The physical interpretation of this equation is that a Bloch electron with wavevector $\boldsymbol{k}$ can have any momentum $\boldsymbol{p}=\boldsymbol{k}+\boldsymbol{G}$, where the probability of finding momentum $\boldsymbol{k}+\boldsymbol{G}$ is proportional to the square of the Fourier coeffients $A_G(\boldsymbol{k})$.

Fig. 1 shows a section of the Fermi surface topology for copper in the repeated zone scheme, where the hatched areas

---

Professor Jochen R. Schneider has been Deputy Director of HASYLAB, DESY, Notkestrasse 85, W-2000 Hamburg 52 since 1989. He is also attached to the Institute of Experimental Physics II, Hamburg University, from which he received his doctorate in 1973 for research at the ILL, Grenoble. He then spent 3 more years, at the ILL, followed by 13 years at the HMI, Berlin, and an academic appointment at the TU Berlin.

Professor Friedhelm Bell has been with the Physics Department, University of Munich, Am Coloumbwall 1, W-8046 Garching since 1978. He studied at the RWTH Aachen and at the University of Cologne, receiving his Ph.D. for work carried out at the MPI für Eisenforschung, Düsseldorf.

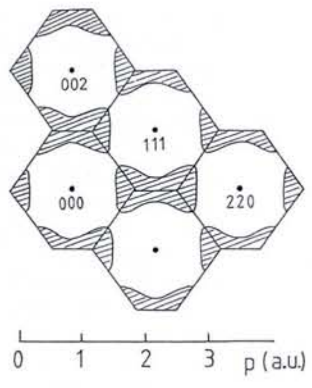


Fig. 1 — Fermi surface topology of copper in the repeated zone scheme. The hatched areas represent the unoccupied p-space regions with respect to the top band. The momentum scale is given in atomic units.

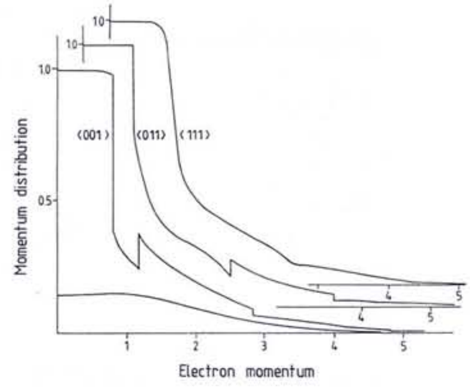


Fig. 2 — Calculated electron momentum density of copper along directions <001>, <011> and <111> [4]. p is in units of $2\pi/a$, with a being the lattice parameter. The lower, smooth curve represents the total calculated contribution of the 3s and 3p bands.

represent the regions of unoccupied states in **p**-space (we discuss the electronic structure of the 3d metal copper as this metal was considered in the past to be a test-bed for new theoretical concepts). The momentum density for the metal, as calculated by the independent-particle model [4], is reproduced in Fig. 2 for the three main crystallographic directions. Interruptions in the density due to the Fermi surface topology are clearly visible, while its profile in the occupied **p**-space regions is determined by the matrix elements $|A_G(\boldsymbol{k})|^2$.

Compton Scattering

The independent-particle model for the momentum density in metals has been very successful in determining Fermi surfaces from two-dimensional positron annihilation data [5]. However, owing to the nature of the positron wavefunction, this approach is of limited value for the study of electron-electron correlation. Modern Compton scattering experiments, on the other hand, prove to be accurate enough to identify these very weak effects.

In a Compton scattering experiment, a collimated beam of monochromatic photons impinges on a sample and the energy distribution of the photons scattered at a fixed scattering angle (typically larger than about 130°) is analyzed. Most experiments have in the past used γ-ray sources, *e.g.*, radioactive ^{197}Au emitting a strong, monochromatic line at 412 keV, and high resolution solid state detectors. Fig. 3 shows the expected energy spectrum of the scattered photons for copper: apart from the well-known shift to lower energies, the spectrum is Doppler broadened due to the velocity distribution of the electrons in the target. Unfortunately, since the recoiling electron is not analyzed in such an experiment, the line shape is determined by the projection of the electron ground-state momentum onto the

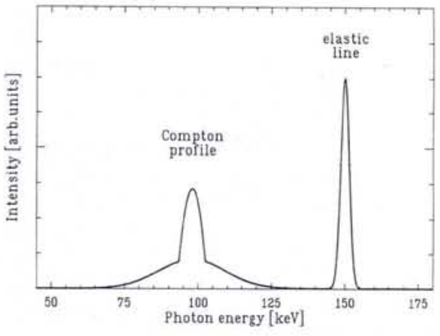


Fig. 3 — Qualitative photon energy spectrum expected if 150 keV photons are Compton scattered by an angle of 140°. The photons loose on average 50 keV which are transferred to the recoiling electrons. Doppler broadening is also observed because of the substantial electron momenta. The inner electrons produce a large broadening, while the contribution of the valence electrons is much narrower and can be separated from the core part by manipulating the data.

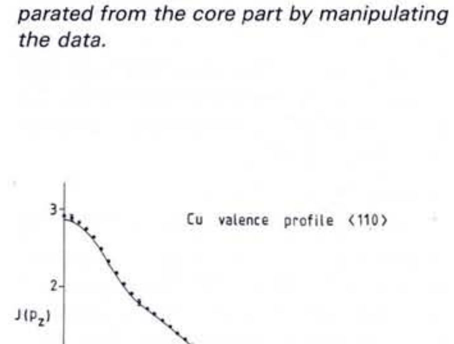


Fig. 4 — The experimental <110> Compton profile for the 11 valence electrons of copper measured with 412 keV γ-radiation [6]. Also shown is the theoretical profile [7] after convolution with the experimental resolution function of FWHM = 0.41 a.u.

scattering vector. If the energy transferred to the electron is much larger than its binding energy, the impulse approximation holds and the measured double-differential cross-section is proportional to the Compton profile, which is a two-dimensional integration of the electron momentum density over a plane perpendicular to the scattering vector **h**.

$$J_h(p_z) = \iint \rho(\boldsymbol{p}) \cdot dp_x dp_y \quad \text{with } \boldsymbol{h} \,||\, p_z.$$

The best momentum resolution obtained with γ-ray Compton spectrometers is 0.4 a.u. (atomic units), corresponding to about 1/5 of the diameter of the Fermi surface of copper. This means that the Compton profile refers to an integration of momentum density over a sheet in **p**-space of 0.4 a.u. thickness. So γ-ray Compton scattering experiments suffer from a low resolution in **p**-space. Fig. 4 shows the valence Compton profile of copper for scattering vector **h** parallel to <110> [6]: compared with the momentum density shown in Fig. 2, the loss of information is dramatic. Nevertheless, these data have allowed a study of electron-electron correlation in copper which will be presented in the next section.

Resolution has been improved to a full-width half maximum (FWHM) of = 0.1 a.u. by using synchrotron radiation and crystal spectrometers as energy analyzers, and further progress is expected in the near future. The pioneering work is by Loupias [8] at LURE in Paris where one has been limited, however, to incident photon energies of <13 keV, thus restricting applications to low atomic number materials. For example, the scattered intensity would be too low for 3d transition elements, notwithstanding the fact that the impulse approximation cannot be fulfilled for the core electrons.

In contrast, 36 directional Compton profiles of vanadium have been measured with 59.4 keV radiation and a resolution of 0.13 a.u. at the National Laboratory for High Energy Physics (KEK) in Japan, where the intention is to reconstruct the three-dimensional momentum density.

Magnetic Compton profiles

Aligned spins induce an asymmetry in the Compton scattered radiation if circular polarized photons are used, and it then becomes possible to measure so-called "magnetic" Compton profiles in ferromagnetic materials

$$J_{mag}(p_z) = \iint [\rho_\uparrow(\boldsymbol{p}) - \rho_\downarrow(\boldsymbol{p})] dp_x dp_y$$

where $\rho_{\downarrow\uparrow}(\boldsymbol{p})$ are the electron momentum densities for spin-up and spin-down electrons, respectively. The pioneering work is due to Sakai [9] who used circular polarized photons from spin-oriented nuclei at low temperature. However, it is only due to the availability of modern synchrotron radiation facilities that the statistical accuracy of data allowed meaningful comparisons with the results of theoretical calculations. A Japanese group uses an intense beam of circular polarized 60 keV X-rays emitted from an elliptical multipole wiggler installed at the 6.5 GeV Accumulator Ring at KEK [10].

For a more exact test of the magnetic properties of solids as calculated by band theory, a group in the UK led by M.J. Cooper, to which we owe the first measurements of magnetic Compton profiles with synchrotron radiation, was able to identify the magnetic contribution to the directional difference Compton profiles in body-centred cubic iron [11].

Electron-Electron Correlation

Opportunities for probing ground-state wave functions of solids *via* Compton scattering at modern synchrotron radiation facilities can be better appreciated by considering electron-electron correlation in copper derived from earlier, low resolution γ-ray Compton data.

Local-density approximation

The most popular approach for describing electron-electron correlation within density-functional theory is the so-called local-density approximation (LDA): remaining discrepancies between experiment and theory are then traced back to shortcomings of LDA in treating many-body effects. The model refers to an homogeneous interacting electron gas and is applicable to systems with slowly varying electron density. It is therefore perhaps surprising that state-of-the-art LDA bandstructure calculations provide reasonable charge densities and total energies, even for 3d transition metals showing relatively strong fluctuations in their valance electron densities.

In a homogeneous interacting electron gas, the occupation numbers $n(\boldsymbol{k})$ are no longer a simple step function, taking values of unity for occupied, and zero for unoccupied states. There is also a finite probability that momentum states outside the Fermi surface are occupied. Fig. 5 shows the electron momentum distributions of free and homogeneous interacting electron gases ($n_o[\boldsymbol{p};\rho(\boldsymbol{r})]$ and $n_h[\boldsymbol{p};\rho(\boldsymbol{r})]$, respectively) for several different electron densities.

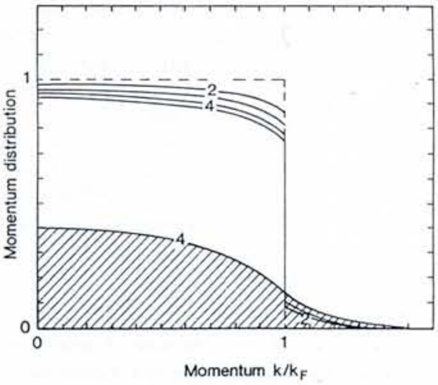


Fig. 5 — Electron momentum distribution of a free (dashed line) and a homogeneous interacting electron gas for different electron densities ρ characterized by the screening radius r_s defined as $(4\pi/3)r_s^3\rho = 1$. The hatched area represents the contribution of many-body effects and k_F is the Fermi wave vector.

Using occupation numbers and the charge density one calculates within LDA the correlation correction term $\Delta\rho(\boldsymbol{p})[\rho]$ according to [12]

$$\Delta\rho(\boldsymbol{p})[\rho] = \int \rho(\boldsymbol{r}) \{n_h[\boldsymbol{p};\rho(\boldsymbol{r})] - n_o[\boldsymbol{p};\rho(\boldsymbol{r})]d\boldsymbol{r}\} \quad (1)$$

which should be added to the momentum density calculated from the eigenfunctions $\phi_i(\boldsymbol{r})$ of the non-interacting Kohn-Sham equations. Incorporating the correlation correction term was done for the first time by Bauer *et al.* [12] for copper and Fig. 6a shows the difference between the experimental <110> valence Compton profile of copper and a LDA calculation [7]. The difference is clearly very much reduced on adding the correlation correction term to the original theoretical Compton profile, demonstrating the importance of the term within LDA in density-functional theory.

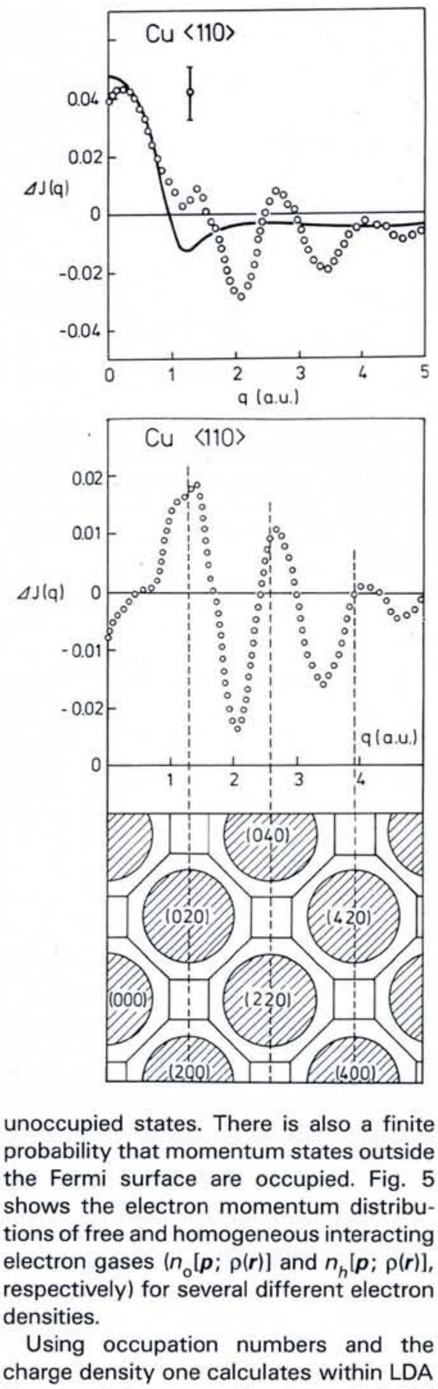


Fig. 6a — Difference $\Delta J = J_{theory}-J_{exp}$ between the Kohn-Sham local-density approximation (LDA) functional bandstructure calculation without the correlation correction term [7] and the experimental <110> Compton profile of copper (open circles). a, upper) The continuous curve represents the correlation correction term calculated according to Eq. (1), which reduces the difference between the full local-density functional theory and experiment significantly. b, lower) ΔJ for the <110> Compton profile of copper. Lower part: xy-plane of the Brioullin zone and the Fermi surface of copper in the repeated zone scheme.

The remaining discrepancies between experiment and theory are illustrated in Fig. 6b, together with the Fermi surface topology for copper in the repeated zone scheme. Whenever the plane of integration perpendicular to <110> (*i.e.*, the transformation of the momentum density into a <110> Compton profile), covers mainly occupied regions in ***p***-space the theoretical values are larger than the experimental ones; in-between the integration is essentially through unoccupied ***p***-space and theory gives low values. This oscillatory behaviour therefore cannot be handled by local-density theory.

Exchange potential

Exchange correlation can affect, in principle, momentum densities *via* the exchange correlation potential $v_{xc}[\rho](\boldsymbol{r})$ and/or the correlation correction term $\Delta\rho(\boldsymbol{p})[\rho]$. Bandstructure calculations for different exchange correlation potentials [13] have shown that discrepancies between experimental and theoretical Compton profiles should be caused by inadequacies in $\Delta\rho(\boldsymbol{p})[\rho]$. The difference between theory and experiment illustrated in Fig. 6b indicates that in the inhomogeneous electron gas, the transfer of momentum density from the occupied Fermi surface into the intervening unoccupied regions is observed not only for the primary Fermi surface, but also for its images centred at reciprocal lattice vectors, *i.e.*, a transfer of momentum density into the interstitial regions where the momentum density is small washes out the contrast predicted by the independent-particle model. The average value of the occupation numbers of the valence electrons inside the Fermi surface has been estimated from an analysis of the value of the autocorrelation function $B(\boldsymbol{r})$ at the lattice translational vector $\boldsymbol{R}_{(110)}$. It differs from unity by about twice the value calculated for the homogeneous electron gas (a similar result has been found in a recent calculation of many-body effects in the momentum density of silicon [14]).

Photon-Electron Coincidence Compton Scattering

The discussion of electron correlation effects in copper suffers from the fact that

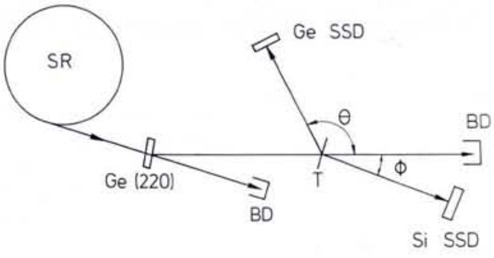
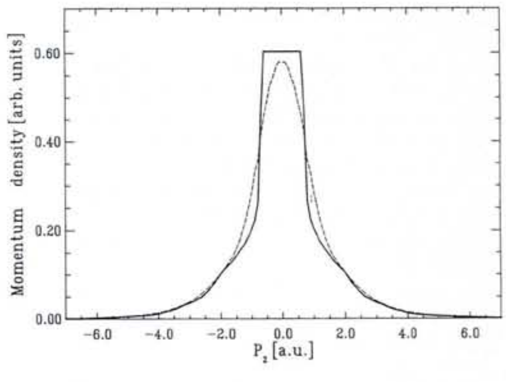


Fig. 7 — Experimental set-up for the (γ, eγ)-experiment at HASYLAB. SR: storage ring; Ge (220): monochromator; BD: beam dump; Ge SSD: photon detector; Si SSD: electron detector; T: target.



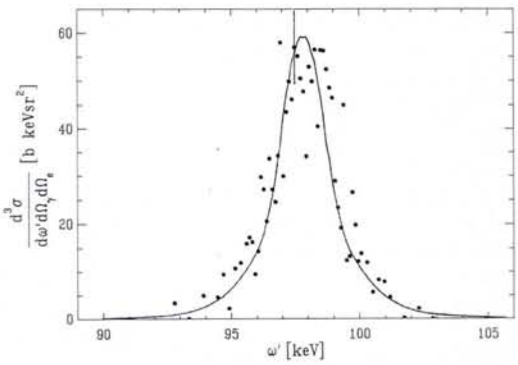


Fig. 8 — Momentum density of copper from photon-electron coincidence Compton scattering. a, upper) The solid line represents the calculated density [4]; the dashed curve is obtained after convolution with a Gaussian of FWHM = 0.5 a.u. to account for instrumental resolution. b, lower) The triple-differential cross-section versus scattered photon energy. Comparison is made between a calculation using the solid state electron momentum density [4] and the results of an experiment performed with 150 keV synchrotron radiation on a 80 nm thick copper target.

Compton scattering experiments integrate over planes in momentum space. Although the momentum density can be reconstructed from a larger number of directional Compton profiles, direct access to $\rho(\boldsymbol{p})$ would be a great advantage. Measuring the Compton scattered photon in coincidence with the recoil electron serves this purpose. The approach is similar to (e, 2e)-scattering which, however, is difficult to apply to solid state targets because of the strong interaction of electrons with matter. We shall summarize the results of initial, exploratory (γ, eγ) photon-electron coincidence Compton experiments performed at HASYLAB [15].

If 150 keV photons are Compton scattered at an angle of 140°, the kinetic energy of the recoiling electron is of the order of 50 keV. Elastic and quasielastic scattering dominate the interaction with the target material at these energies, and the mean free path has been estimated as 12 nm for copper. In order to limit the effect of multiple electron scattering, a self-supporting, polycrystalline Cu foil of 80 nm thickness has been used in a coincidence Compton experiment. The effective sample thickness is four orders of magnitude smaller than in ordinary γ-ray experiments so high intensity incident photon beams are needed, which only modern synchrotron radiation sources can provide.

Fig. 7 shows the experimental set-up: the photon detector, an intrinsic Ge diode with a resolution of FWHM ≈ 0.5 keV at 100 keV, was positioned at a scattering angle of 140°. The electron detector, an implanted planar Si diode with a resolution of FWHM ≈ 7 keV could be moved through an angular range of $\Delta\phi = \pm 10°$ around an recoil electron scattering angle $\phi = 15.8°$. The electron momentum density can be scanned in two different ways [16]:

– For fixed scattering angles, one measures the *Doppler broadening* in the photon or in the electron detector resulting from intrinsic electron momentum components p_z lying parallel to the momentum transfer vector.

– For fixed energies, one measures the *angular correlation* between the photon scattered at an angle θ and the recoil electron scattered at an angle ϕ; the momentum density is thus sampled for electron momenta $p_\perp$ perpendicular to the momentum transfer vector.

Fig. 8a compares experimental results with the spherically averaged electron momentum density of copper calculated by Bross [4]: owing to the low momentum resolution of $\Delta p_z = 0.9$ a.u., the prominent features predicted for low momenta are smoothed out in the coincidence experiments. Improvements to the experimental arangement will help overcome this limitation. Progress has already been made by inserting a focussing monochromator to improve the energy spread of the incident beam by almost a factor of two without loosing intensity. In addition, a position-sensitive electron detector has been developed which accepts a smaller solid angle per pixel, so that momentum resolutions $\Delta p_\perp \approx 0.5$ a.u. and $\Delta p_z \approx 0.4$ a.u. are within reach.

Momentum densities (*e.g.*, Fig. 8a) are generally measured on a relative scale and data processing normalizes them to the number of electrons. In contrast, the solid line in Fig. 8b shows absolute values of the triple-differential cross-section for (γ, eγ)-scattering *versus* the scattered photon energy, as measured by us for the first time (the data have been converted into cross-sections by comparing single photon count rates with the well-known, double-differential cross-sections): measured and calculated cross-sections agree within the estimated errors.

Today's (γ, eγ)-scattering experiments suffer from poor statistics: more intense sources of high energy synchrotron radiation are needed to fully exploit the potential of this novel solid state spectroscopy. We present on page 14 a proposal for a fourth-generation source based on inserting undulator structures into the straight sections of DESY, Hamburg's, PETRA storage ring. This source would provide a beam of high energy synchrotron radiation with an intensity some four orders of magnitude above present levels, and significantly higher than the intensities which will eventually become available at third-generation sources now being built.

Conclusions

Different theoretical models have been developed to incorporate many-body effects into calculations of the electronic structures of solids. Their success is judged by the extent to which theory reproduces experimental data. γ-ray Compton scattering has already proved its value in probing ground-state wavefunctions, but the technique can be developed further with the availability of modern synchrotron radiation facilities.

A new approach, where the Compton scattered photon is measured in coincidence with the recoiling electron, allows a direct determination of electron momentum densities in solids. This (γ, eγ)-scattering method will reach its full potential once synchrotron radiation from undulators in electron storage rings operating at energies above 10 GeV becomes available.

REFERENCES

[1] Kohn W. and Sham L.J., *Phys. Rev. A* **140** (1965) 1133; Hohenberg P. and Kohn W., *Phys. Rev. B* **136** (1964) 864.

[2] Bauer G.E.W., *Phys. Rev. B* **27** (1983) 5912.

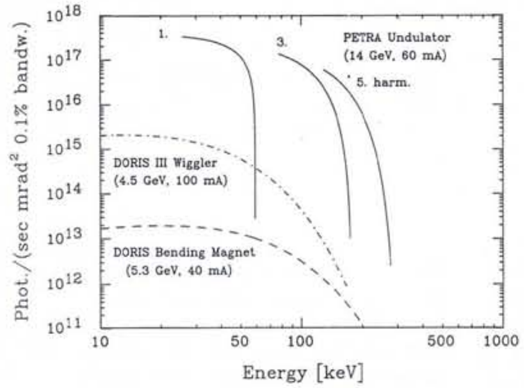
[3] Schülke W. and Mourikis S., *Acta Cryst. A* **42** (1986) 86.
[4] Bross H., *J. Phys. F* **12** (1982) 2249.
[5] Berko S. in *Positron Solid State Physics*, Proc. Int. School of Physics "Enrico Fermi", Eds. W. Brandt and A. Dupasquier (North-Holland, Amsterdam) 1983.
[6] Pattison P., Hansen N.K. and Schneider J.R., *Z. Physik B* **46** (1982) 285.
[7] Bagayoko D. *et al.*, *Phys. Lett. A* **76** (1980) 187.
[8] Loupias G. *et al.*, *Phys. Stat. Sol. (b)* **102** (1980) 79.
[9] Sakai N. and Ono K., *Phys. Rev. Lett.* **37** (1976) 351.
[10] Yamamoto S. *et al.*, *Phys. Rev. Lett.* **62** (1989) 2672.
[11] Cooper M.J. *et al.*, *Phys. Rev. B* **34** (1986) 5984; Collins S.P. *et al.*, *J. Phys.: Cond. Matter* **1** (1989) 9009.
[12] Lam L. and Platzman P.M., *Phys. Rev. B* **9** (1974) 5122; Bauer G.E.W. and Schneider J.R., *Phys. Rev. B* **31** (1985) 681.
[13] Bauer G.E.W. and Schneider J.R., *Z. Physik B* **54** (1983) 17.
[14] Charlesworth J.P.A. *et al.*, *Proc. 20th Int. Conf. on the Physics of Semiconductors* (World Scientific) 1991.
[15] Bell F. *et al.*, *J. Phys.: Cond. Matter*, in print.
[16] Bell F. *et al.*, *Phys. Rev. B* **41** (1990) 4887.

REPLACEMENT

A few copies of *EN* (**22**, December) 1991 contained duplicates of pp. 209-212 instead of pp. 205-208. We apologize for the error. Please contact the Secretariat for replacements.

PETRA By-Pass

A Fourth Generation Synchrotron Source



Brightness of a 5 m long undulator which could be installed at DESY, Hamburg, in a by-pass of HERA's PETRA booster storage ring. The solid lines represent the brightness of the first, third and fifth harmonics of the undulator as a function of the size of the magnetic gap. Comparisons are made with the performance of a wiggler and a bending magnet presently installed at HASYLAB's DORIS storage ring.

Storage rings operated above 10 GeV at ep-colliders offer attractive possibilities for fourth-generation synchrotron radiation sources. In particular, the storage ring PETRA has recently been reconstructed as an electron and proton booster for HERA, the new, superconducting hadron-electron storage ring at DESY, Hamburg (Ed.: HERA obtained its first beam last October). The expected lifetimes in HERA are 3 hours for electrons, and 12 hours for protons. PETRA could be used between injections as a storage ring for synchrotron radiation without affecting its performance as a booster for HERA.

A by-pass for synchrotron radiation experiments at PETRA has been proposed [Brefeld W. and Gürtler P., *Proc. Particle Accelerator Conf.*, Stanford, USA (1991)] which would provide space for the installation of two 5 m long magnetic undulators. At 13 GeV, the existing electron booster optics yields an emittance of 79 nmrad: the photon beam divergence would be 0.053 mrad by 0.012 mrad and the beam size some 12 × 2.7 mm² at a point 100 m from the undulator. The figure shows the spectral brightness calculated for an undulator using hybrid technology (permanent magnets and electromagnets) with a period of 3.35 cm and a gap of 11 mm, operated at an electron energy of 14 GeV. By opening the gap, the energy of the photons from the fundamental can be tuned between 20 and 40 keV with almost constant intensity. Including third and fifth harmonics, the energy range from 20 to 200 keV is covered by one device. The total radiation power emitted by this undulator is 13.7 kW, but only 130 W are emitted in the energy range up to 5 keV. Filters can therefore be used and handling of the heat load is straight-forward.

J.R. Schneider, F. Bell

EPS/JPS Collaboration

Meeting in Budapest with Maurice Jacob, President of EPS, on the occasion of the 100th anniversary of the Eötvös Physical Society, Professor Mishiji Konuma, President of **The Japan Physical Society** agreed to work to establish a direct and permanent contact between the two Societies. Link persons responsible for exchanging information and corodinating activities have been nominated. They are the JPS Secretary for International Affairs (currently Dr. Ken Kikuchi, of KEK Tsukuba) and the Vice-Secretary of the EPS Executive Committee (currently, Professor A. Taroni, Facolta di Ingegneria, via Valotti, 9, I-25100 Brescia), who can be contacted by members concerning questions for which the advice of the JPS is important.