XIII School on Synchrotron Radiation:
Fundamentals, Methods and Applications
Grado, Italy / 14-25 September 2015

Photoemission Spectroscopy: Fundamental Aspects

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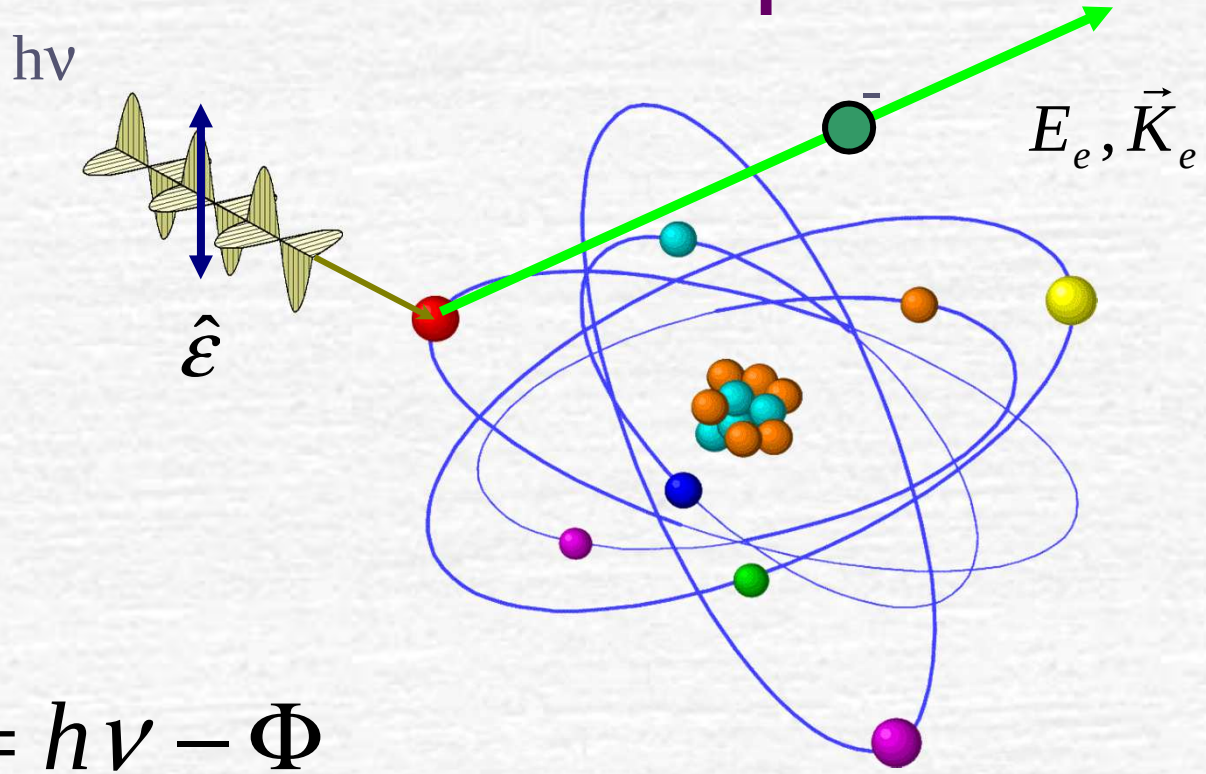
Basic Concepts



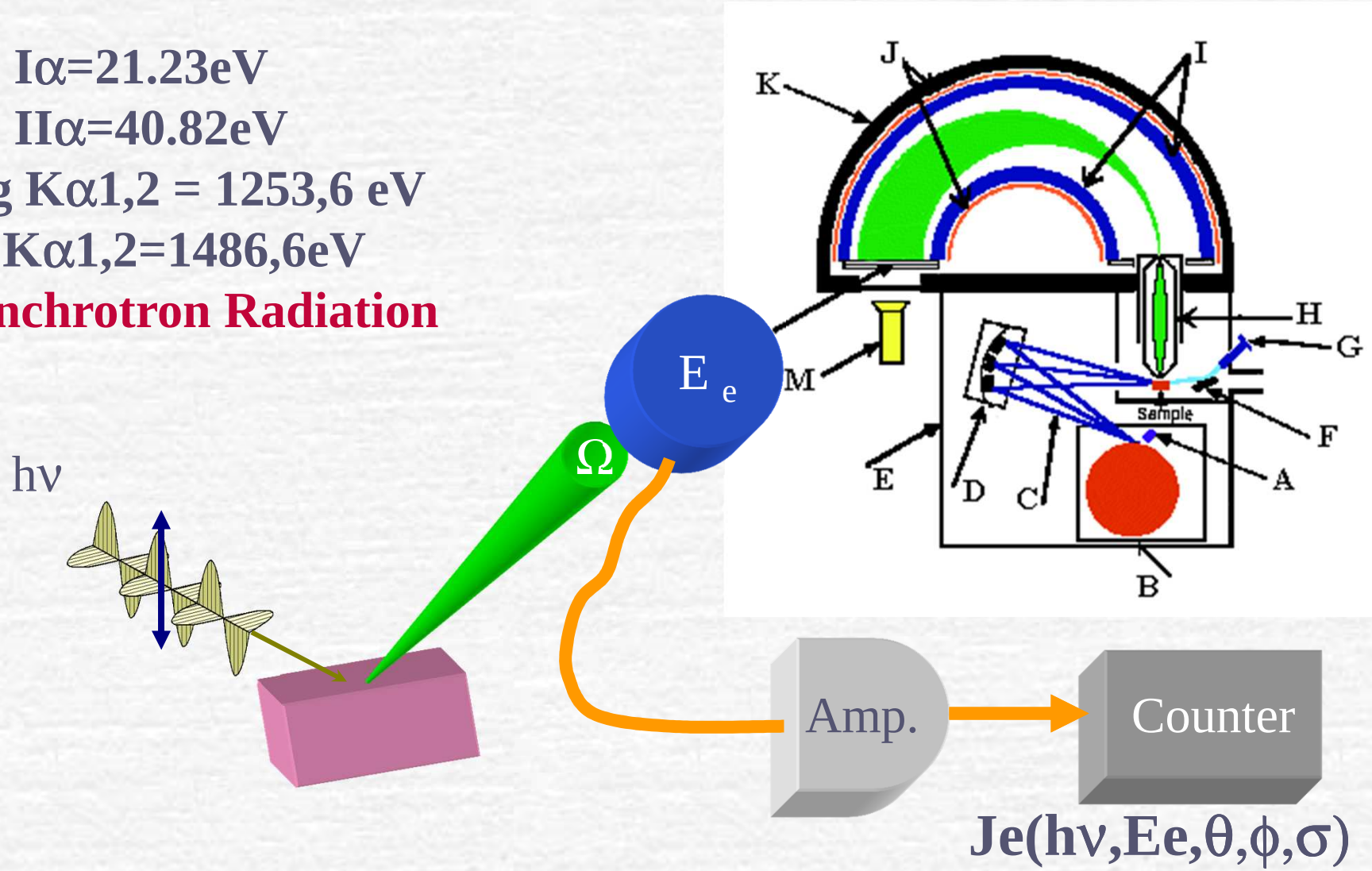
$$E_e^{MAX} = h\nu - \Phi$$

outline

1. Intruduction
2. Energy conservation, binding energy and photoelectron energy
3. Satellite structures and multiplet splitting
4. Chemical shift
5. Molecular photoelectron spectra
6. Photoelectron angular distributions
7. Hole state relaxation
8. Resonant photoemission
9. Photoemission in solids
10. EDC and core ionization
11. Angular resolved PES

Photoemission Schematics:

He Iα=21.23eV
He IIα=40.82eV
Mg Kα1,2 = 1253,6 eV
Al Kα1,2=1486,6eV
Synchrotron Radiation

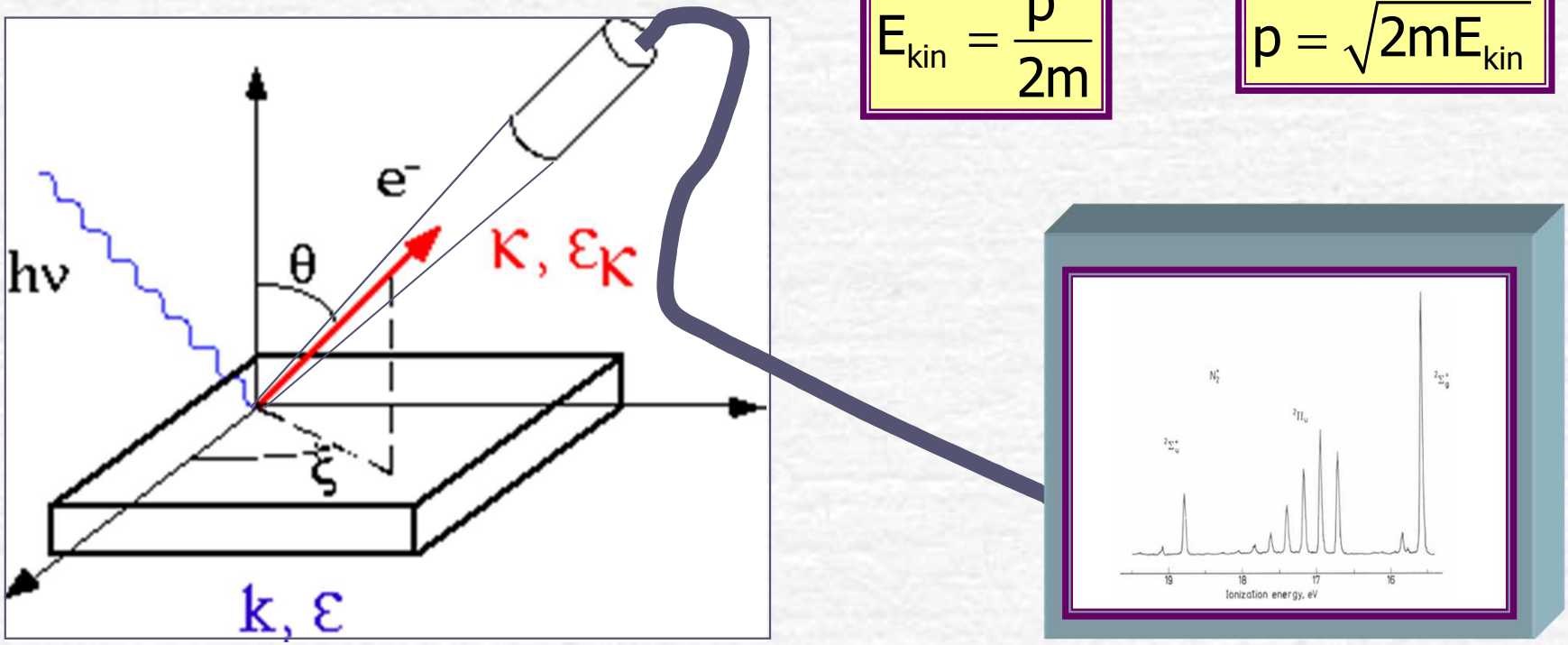


ENERGY CONSERVATION, BINDING ENERGY AND PHOTOELECTRON ENERGY

$$E_{kin} = \hbar\omega - \phi - |E_b|$$

$$E_{kin} = \frac{p^2}{2m}$$

$$p = \sqrt{2mE_{kin}}$$



X-section vs. Photoemission current

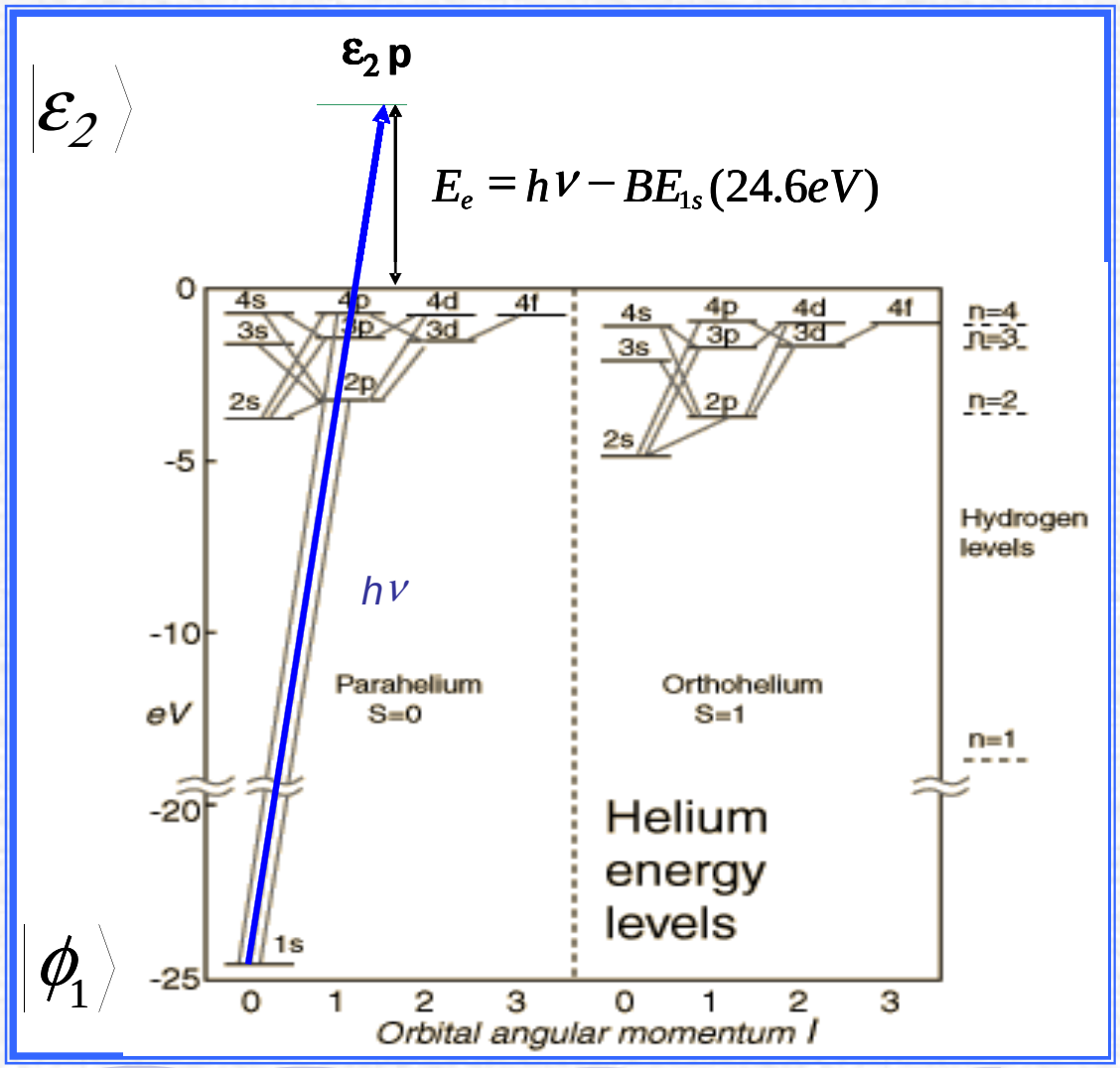
$$J_e(h\nu,\vartheta,\phi) = J_{h\nu}(\rho l)\int_{\Delta E\Delta\Omega}\int \frac{d\sigma}{d\Omega dE} F_{an}(E,\Omega)\eta_{\det}(E)d\Omega dE$$

Photoemission peak lineshape

1. **Photon monochromaticity** — **Gaussian**
2. **Electron analyzer resolution** — **Gaussian**
3. **Final state lifetime (uncertainty principle)** — **Lorentian**

Lineshape =Convolution (1,2,3)

The photoemission process



$|\Psi_a\rangle$

$1s^2$

$^1S_0$

Interaction radiation matter

$$\frac{d\sigma}{dh\nu} = 4\pi^2 \alpha h\nu \sum_B \left| \hat{\varepsilon} \bullet \left\langle \Psi_B \left| \sum_i \vec{r}_i \right| \Psi_A \right\rangle \right|^2 \delta(E_B - E_A - h\nu)$$

Bertoni's lecture this school

Initial state A = Neutral ground(excited) state
Final state B = Residual ion + free electron(s)

Energy balance for 2e atom

$$E_B = E_A + h\nu$$

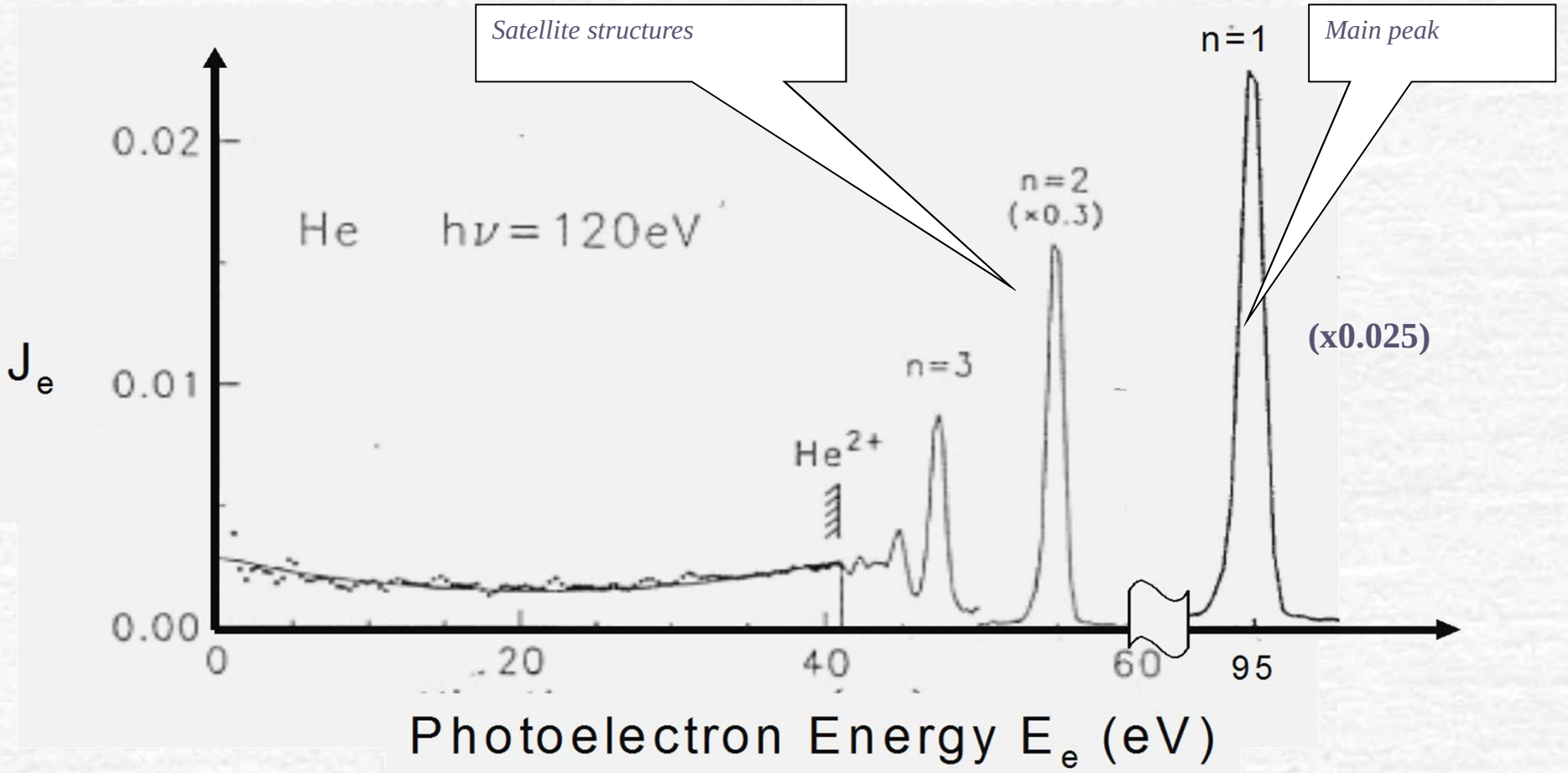
$$\Psi_A = \hat{A}\phi_1\phi_2 \qquad \Psi_B = \hat{A}\phi_1\varepsilon_2$$

$$E_{1s} + E_e = E_{1s} + E_{1s} + h\nu$$

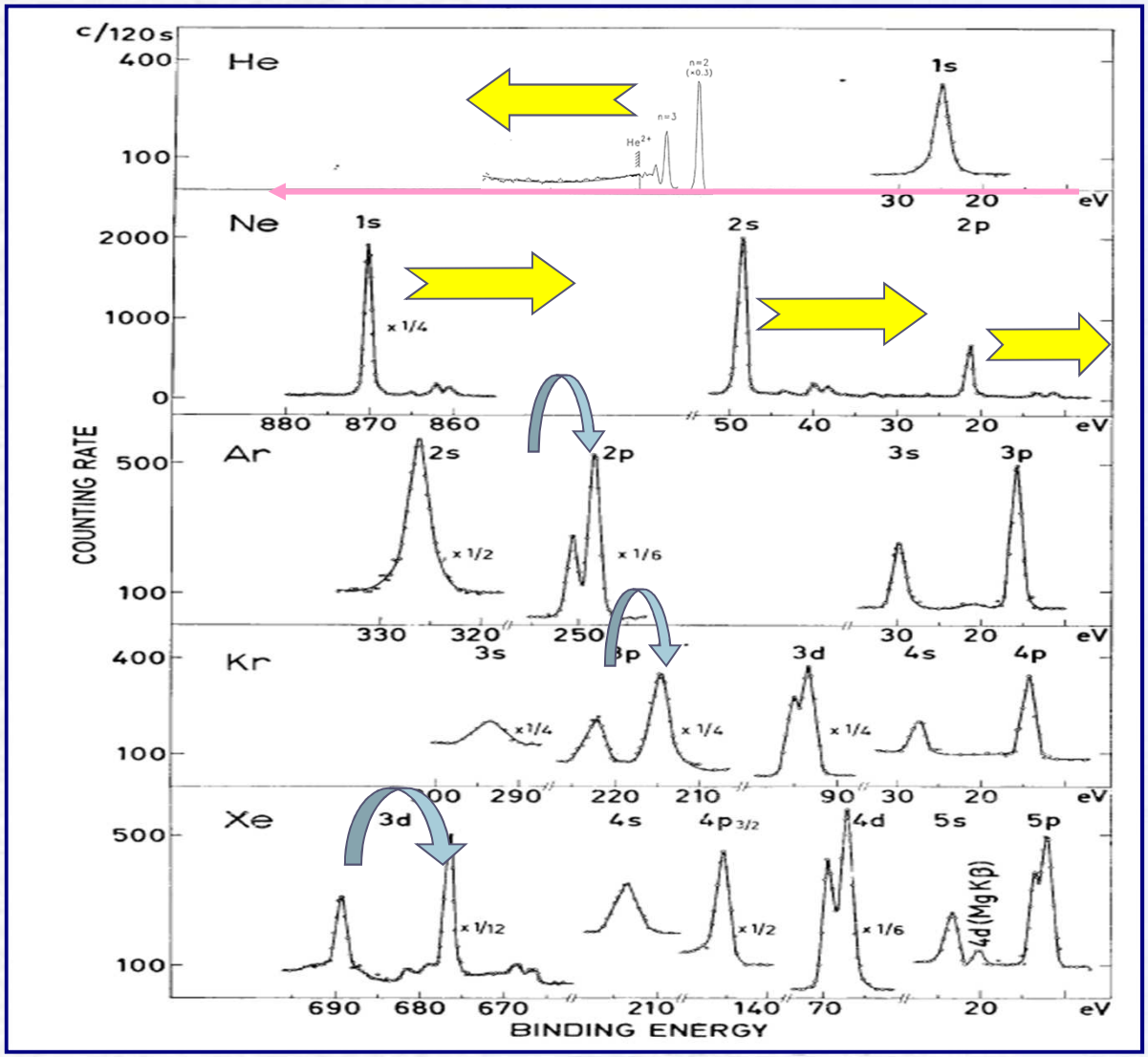
$$E_e = h\nu - BE_{1s}\,(24.6eV)$$

One single photoemission peak is expected
Energy and momentum are conserved

Complexity of the photoemission spectrum



The noble gas panorama



He $1s^2$

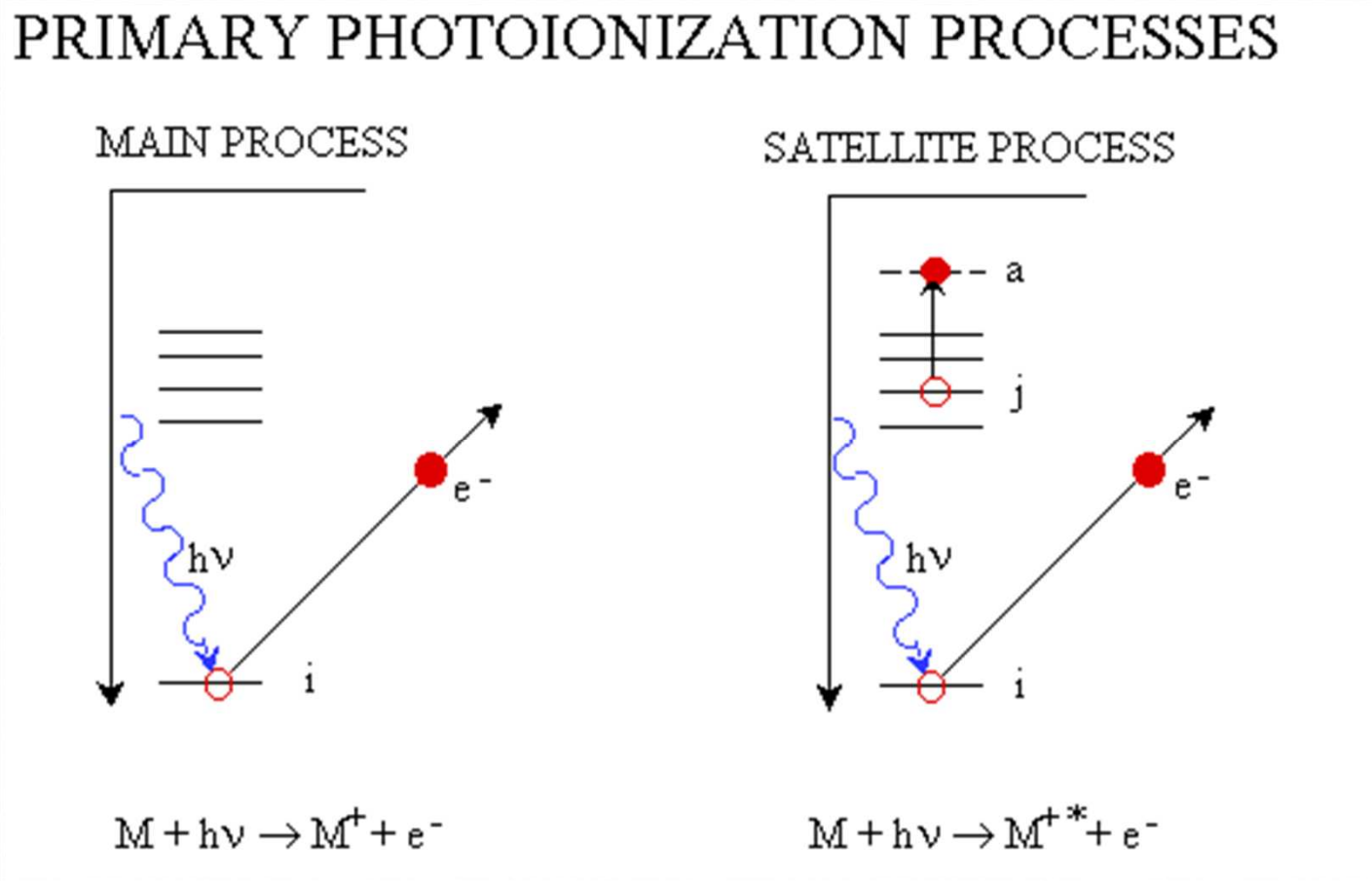
Ne $1s^2\ 2s^2\ 2p^6$

Ar $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6$

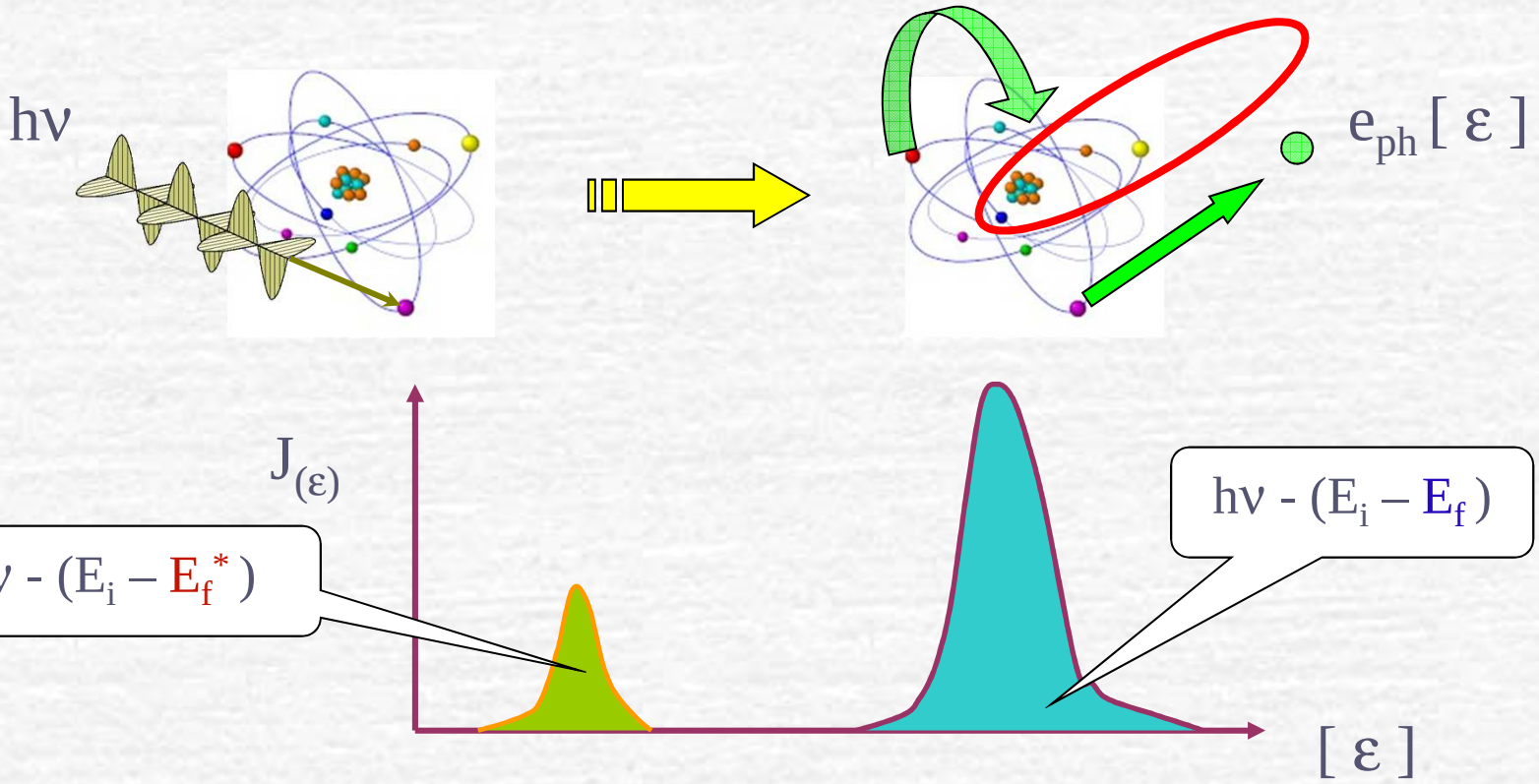
Kr $1s^2.:.3s^23p^63d^{10}\ 4s^24p^6$

Xe $\ldots 3d^{10}4s^24p^64d^{10}5s^25p^6$

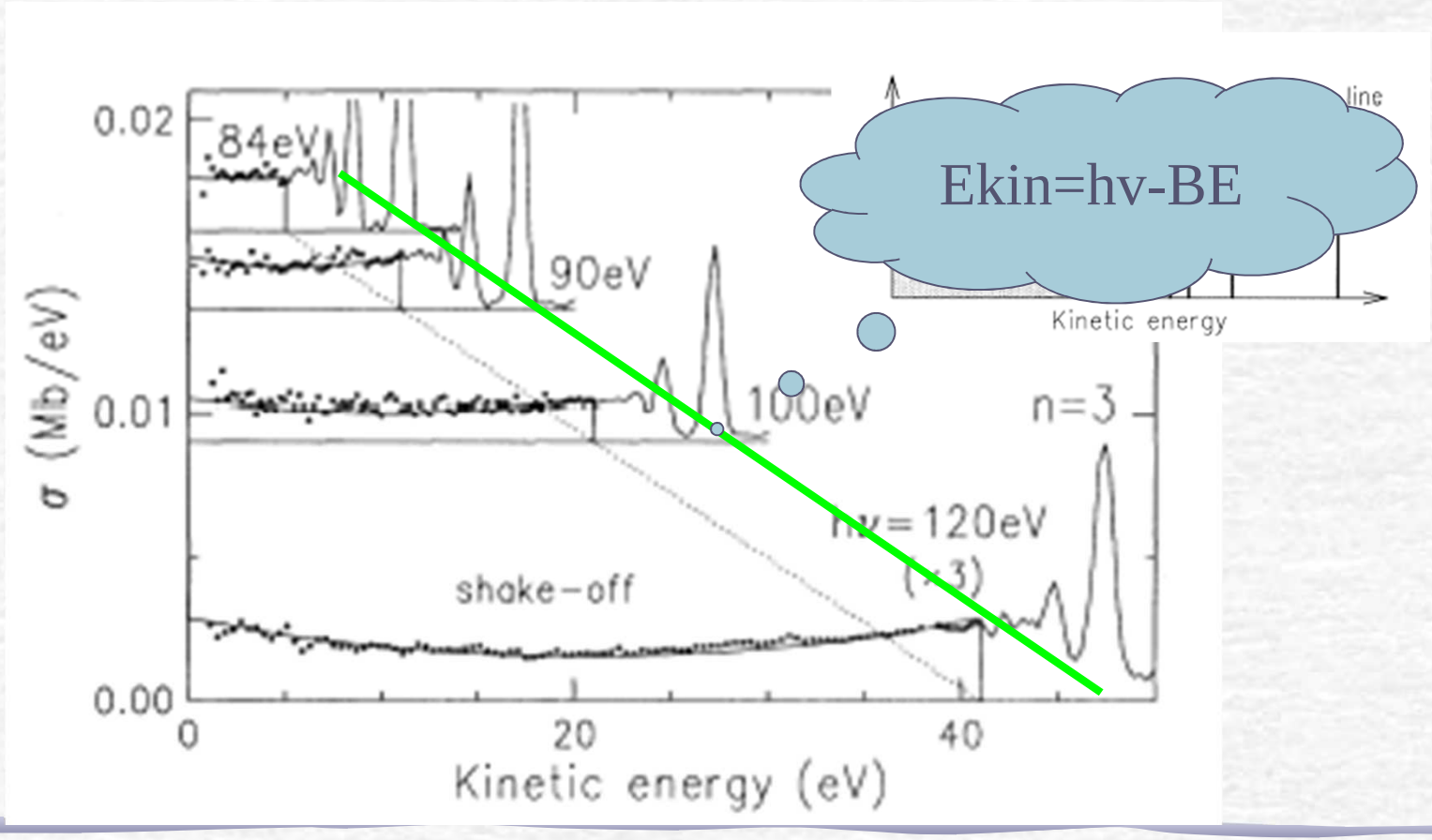
Primary photoionization process



- Photon = single particle operator
- 2 or more particles involved in final state = e-e correlation
- Relaxation & e-e correlation in photoemission = satellite



The He satellite structure



A many electron atom

$$H_0 \left| \Psi_A^{(N)} \right\rangle = E_A^{(N)} \left| \Psi_A^{(N)} \right\rangle$$

$$H_0 = H_0(kin) + H_0(e-n) + H_0(e-e) + H_0(s-o) =$$

$$= \sum_1^N \frac{p_i^2}{2m} + \sum_1^N - \frac{Ze^2}{r_i} + \sum_{i>j}^N \frac{e^2}{r_{ij}} + \sum_1^N \zeta(r_j)\vec{l}_i \bullet \vec{s}_i$$

$$\left| \Psi_A^{(N)} \right\rangle = \hat{A}(\phi_j(\vec{r}_i, \sigma_i); \Psi_R^{(N-1)})$$

Single particle orbital

$$H_0^{'} \left| \Psi_B^{(N)} \right\rangle = E_B^{(N)} \left| \Psi_B^{(N)} \right\rangle$$

sudden approximation

$$\left|\Psi_B^{(N)}\right\rangle = \hat{A}(\varepsilon_l ; \left|\Psi_B^{(N-1)}\right\rangle)$$

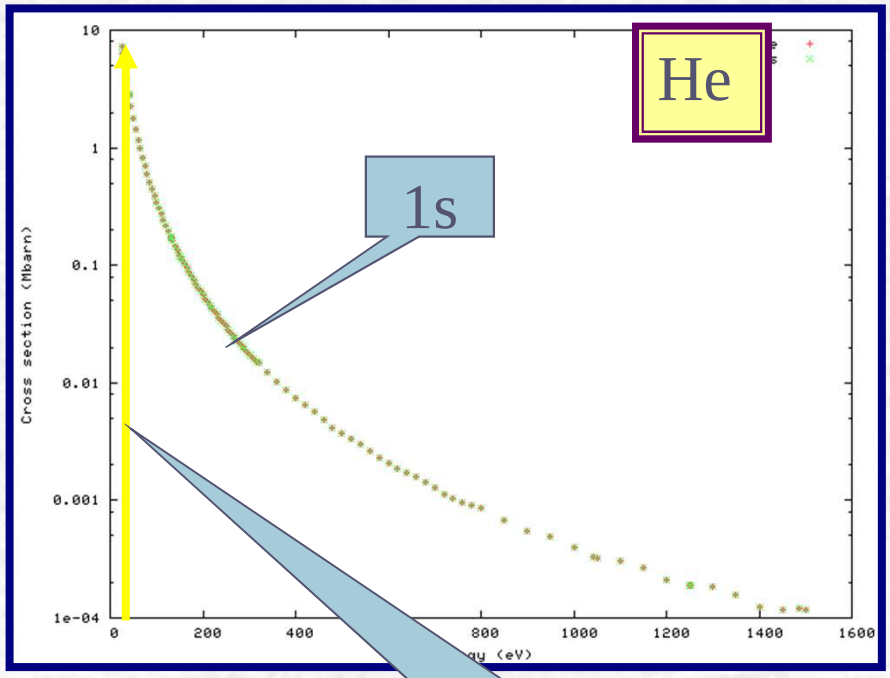
$$\frac{d\sigma}{d\Omega dE_e} \propto \frac{1}{h\nu}\sum_{A,B}\left|\hat{\varepsilon}\bullet\left\langle\varepsilon_l\left|\vec{r}_j\right|\phi_j(\vec{r}_j,\sigma_j)\right\rangle\left\langle\Psi_B^{(N-1)}\left|\Psi_R^{(N-1)}\right\rangle\right|^2\delta(E_e+E_B^{(N-1)}-E_A-h\nu)$$

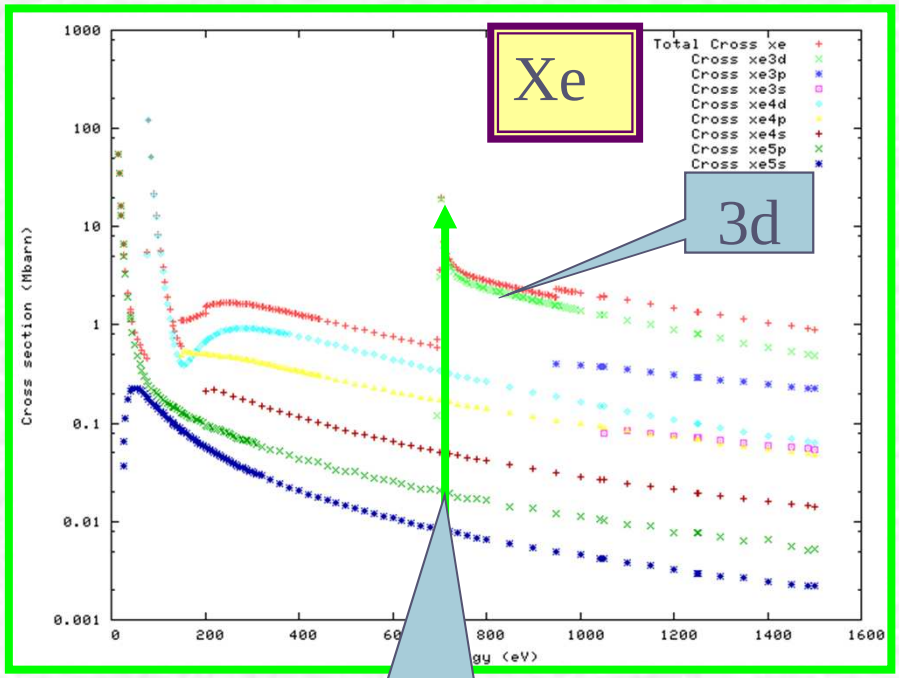
frozen core approvimation

$$H_0^{'} = H_0$$

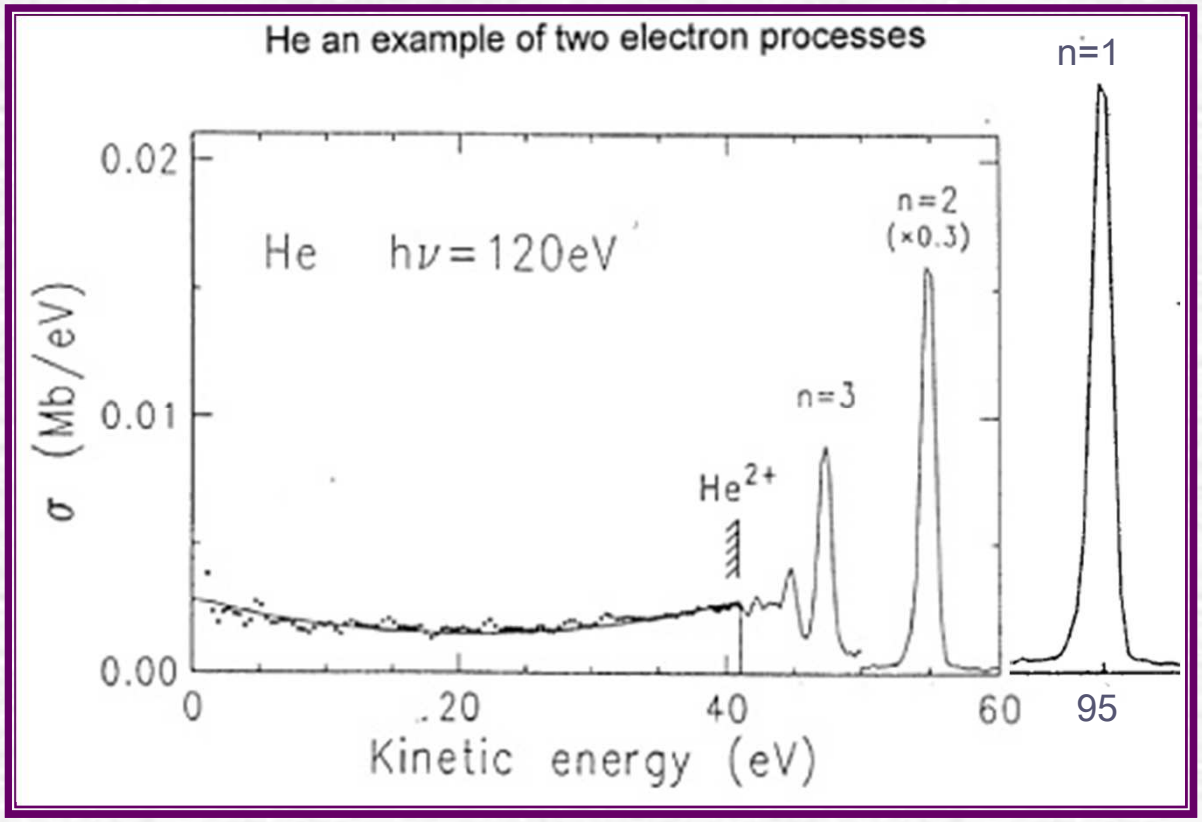
$$\frac{d\sigma}{d\Omega dE_e} \propto \frac{1}{h\nu}\sum_{A,B}\left|\hat{\varepsilon}\bullet\left\langle\varepsilon_l\left|\vec{r}_j\right|\phi_j(\vec{r}_j,\sigma_j)\right\rangle\right|^2\delta(E_e+\varepsilon_j-h\nu)$$

Total photoemission cross section





Photoelectron current vs. photoelectron energy



Monopole and dipole selection rules

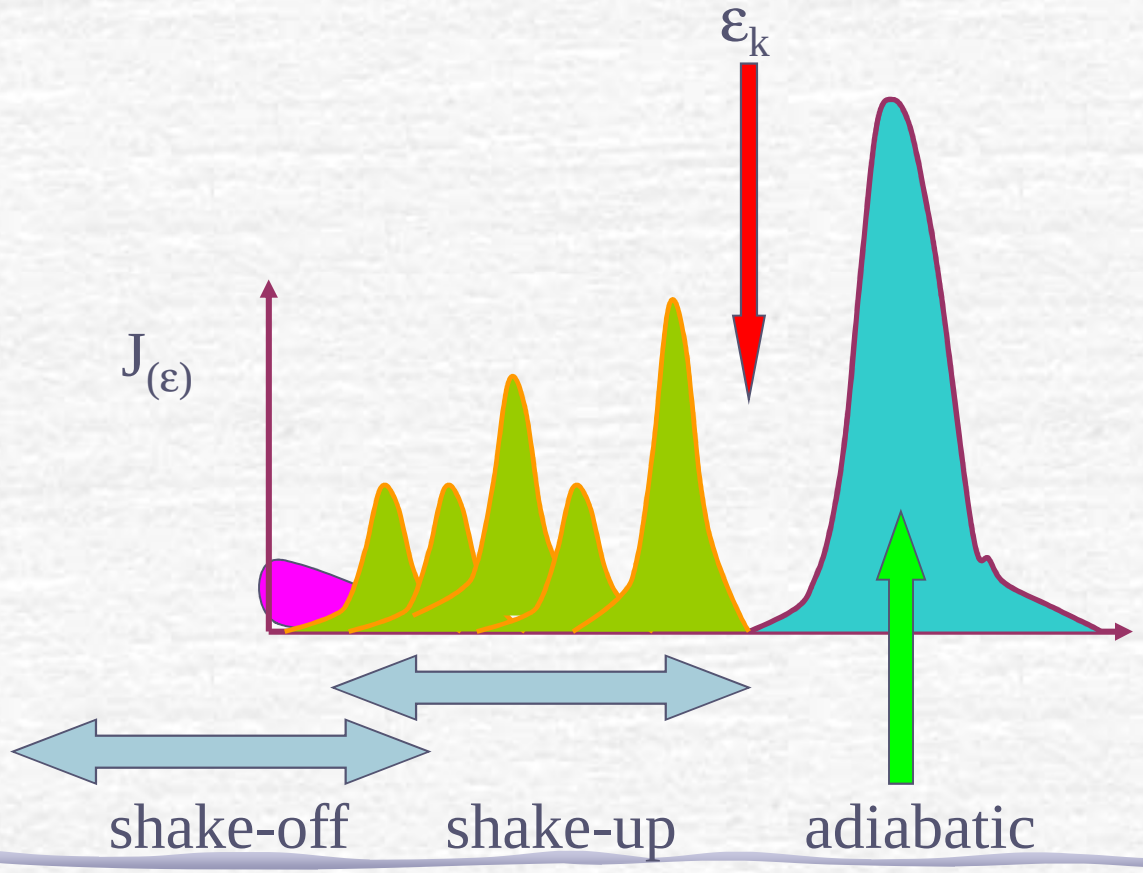
$$h\nu + He(1s^2) \rightarrow He^+(1s^1) + \varepsilon_{\ell=1}$$

$$h\nu + He(1s^2) \rightarrow He^+(2s^1) + \varepsilon_{\ell=1}, He^+(3s^1) + \varepsilon_{\ell=1}, He^+(4s^1) + \varepsilon_{\ell=1}, \ldots\ldots\ldots\ldots He^{++} + \varepsilon_{\ell} + \varepsilon_{\ell'}$$

$$h\nu + He(1s^2) \rightarrow He^+(2p^1) + \varepsilon_{\ell=0}, He^+(3p^1) + \varepsilon_{\ell=0}, He^+(4p^1) + \varepsilon_{\ell=0}, \ldots\ldots\ldots He^{++} + \varepsilon_{\ell} + \varepsilon_{\ell'}$$

Koopmans energy vs. photoemission peaks

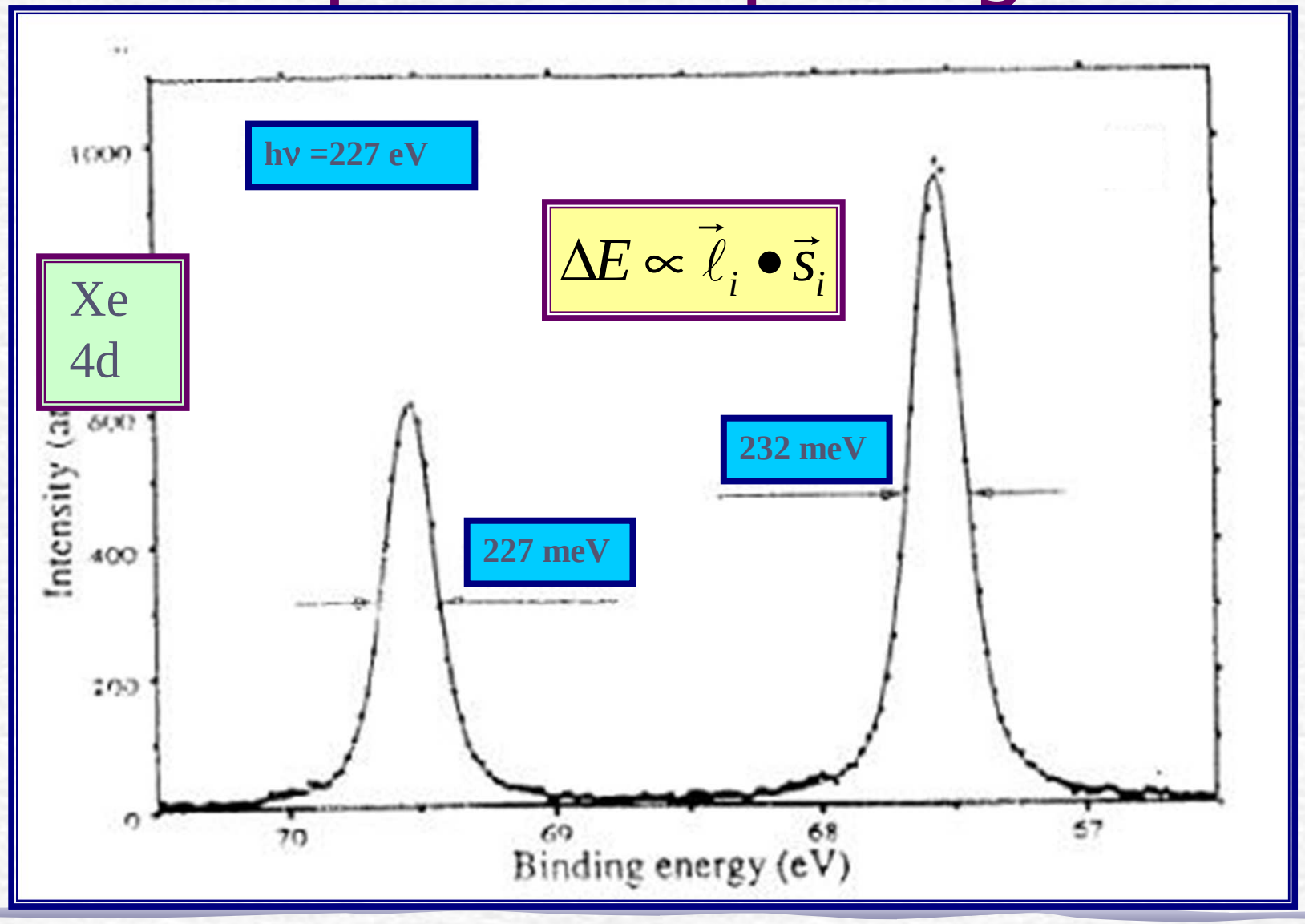
$$\frac{d\sigma}{d\Omega dE_e} \prec \frac{1}{h\nu}\sum_{A,B}\left|\hat{\varepsilon}\bullet\left\langle\varepsilon_i\left|\vec{r}_j\right|\phi_j(\vec{r}_j,\sigma_j)\right\rangle\left\langle\Psi_B^{(N-1)}\left|\Psi_R^{(N-1)}\right\rangle\right|^2\delta(E_e+E_B^{(N-1)}-E_A-h\nu)$$



$$\varepsilon_k = \frac{\sum_i \varepsilon_i I_i}{\sum_i I_i}$$

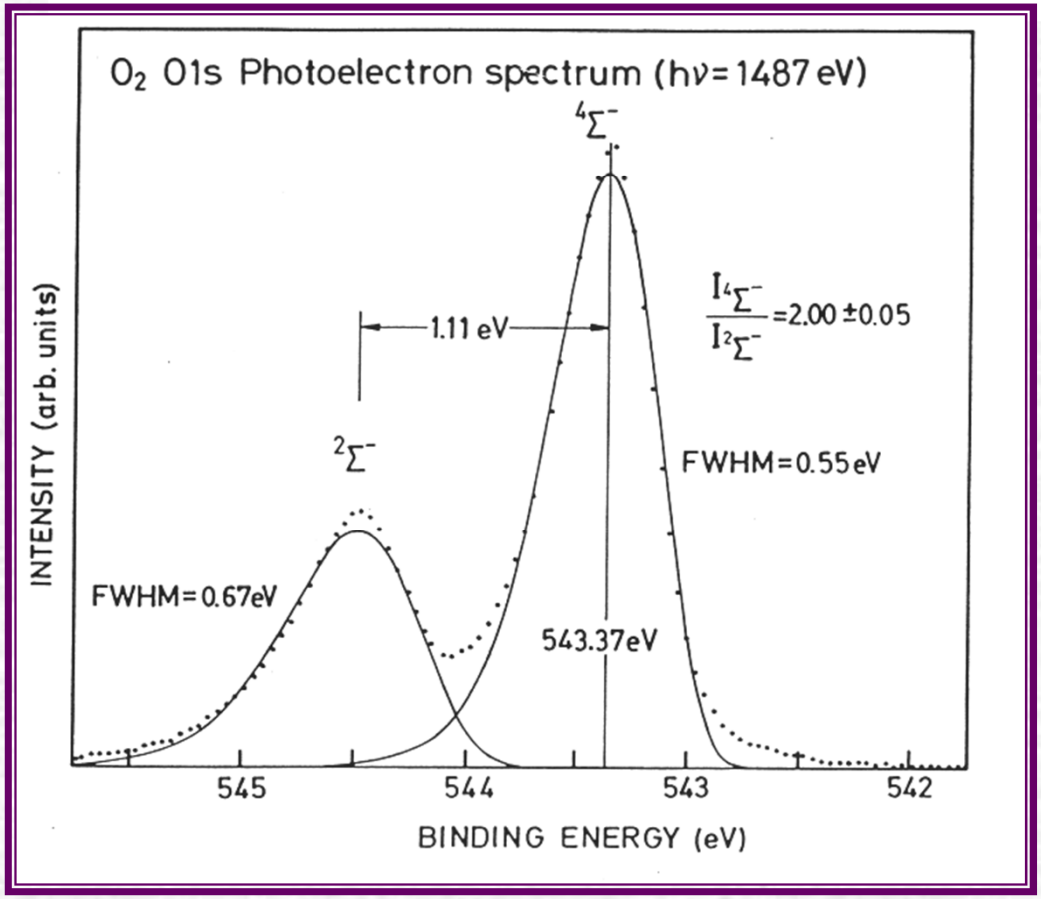
$$E_{relax} = \varepsilon_{adiab} - \varepsilon_k$$

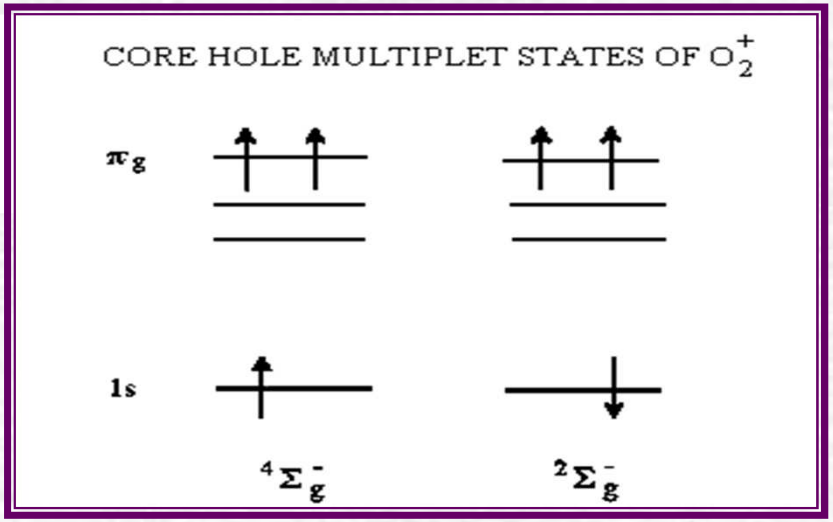
Spin orbit splitting

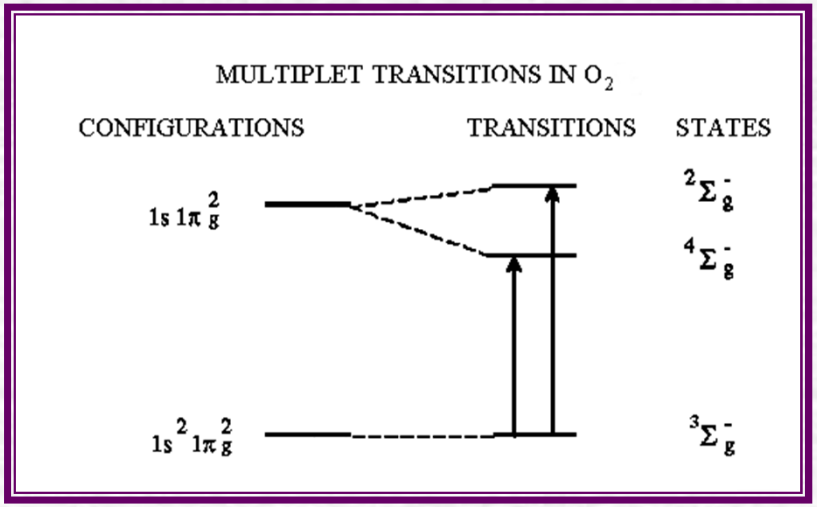


Molecular multiplet splitting O_2

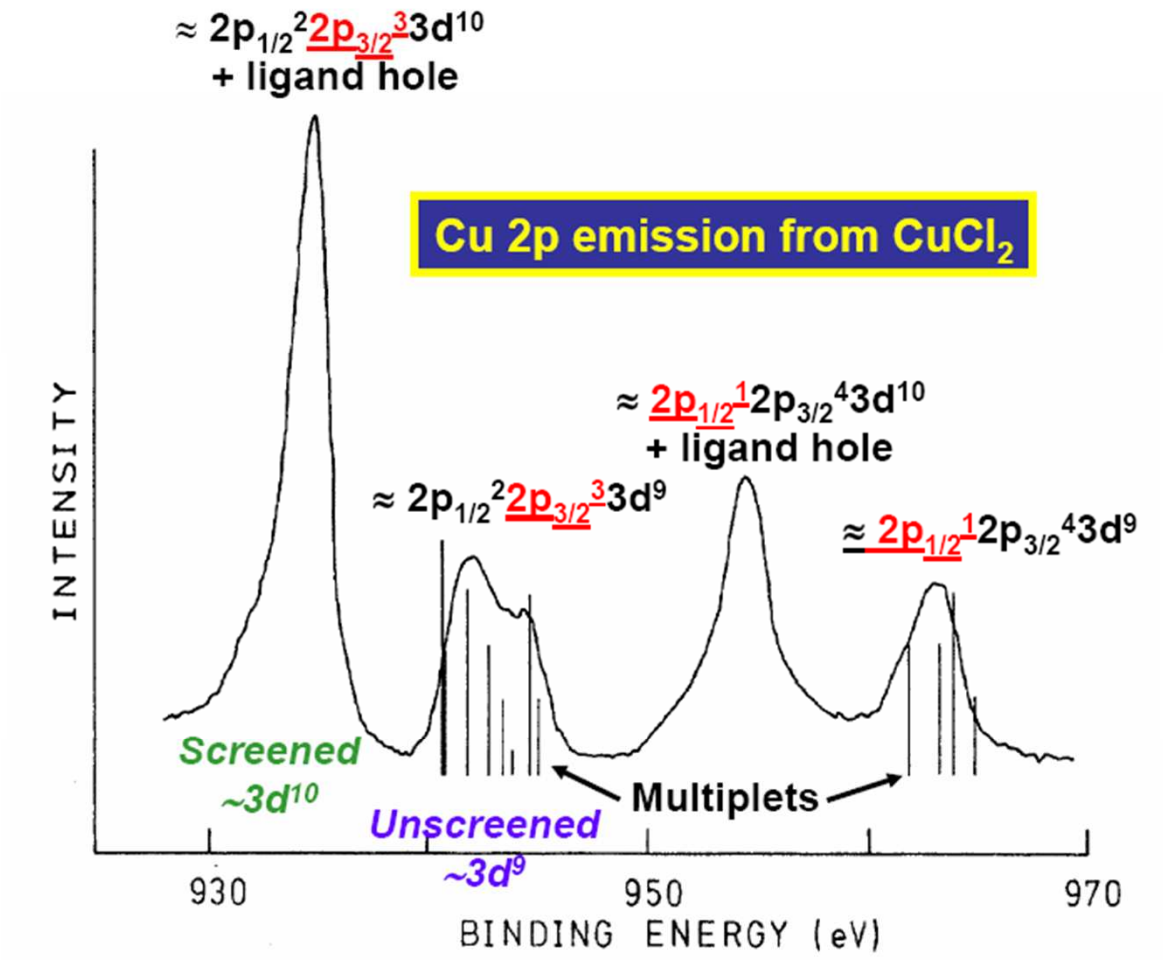
$$KK(\sigma_g 2s)^2 (\sigma_u 2s)^2 (\sigma_g 2p)^2 (\pi_u 2p)^4 (\pi_g 2p)^2 \ ^3\Sigma_g^-$$







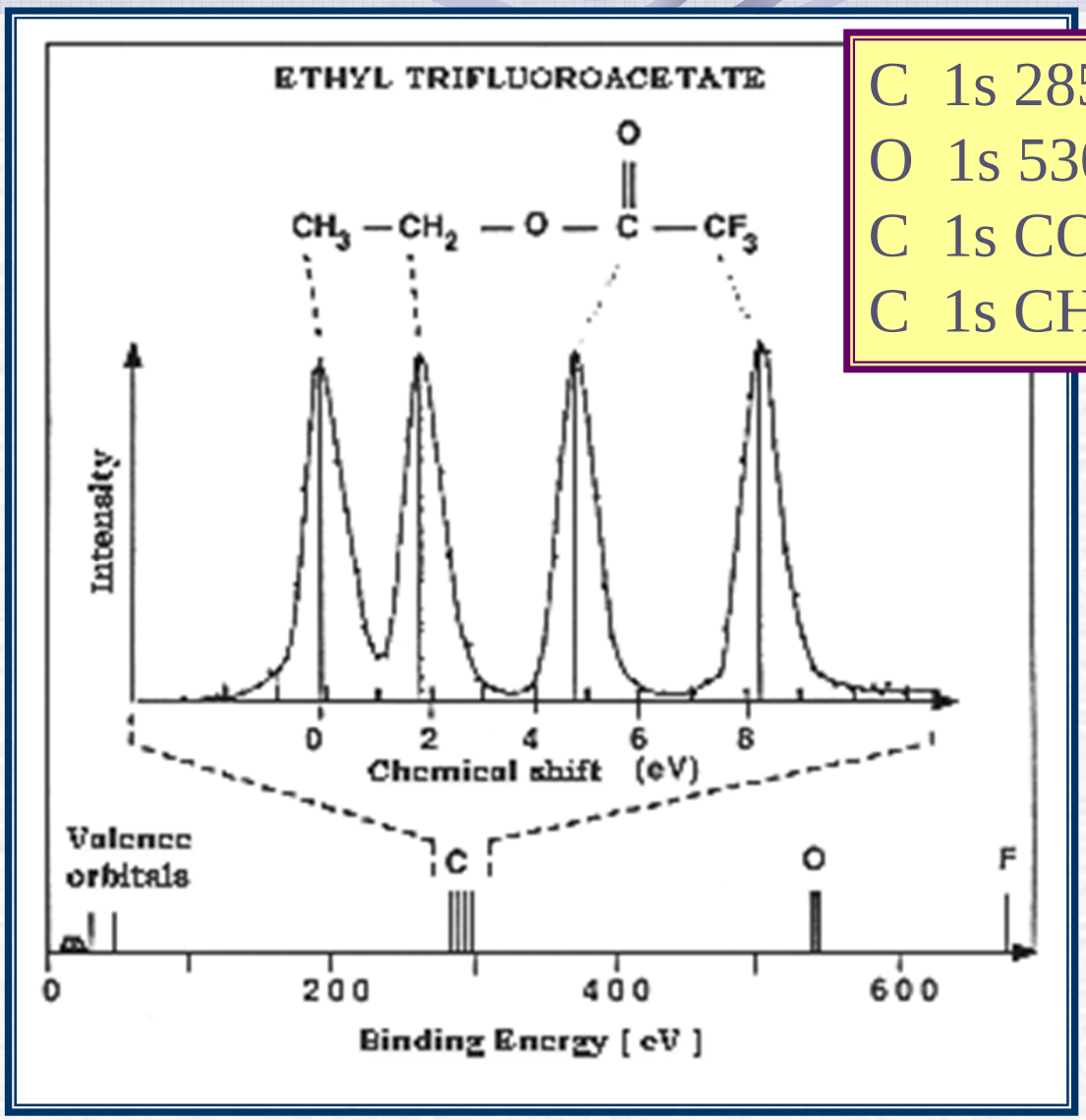
$CuCl_2$ multiplet & satellite



$$\Psi_{final,K}(N-1) = C_{1,K}(2p_{1/2}^2 2p_{3/2}^3 3d^{10} + C\ell\ hole) + C_{2,K}(2p_{1/2}^2 2p_{3/2}^3 3d^9)$$

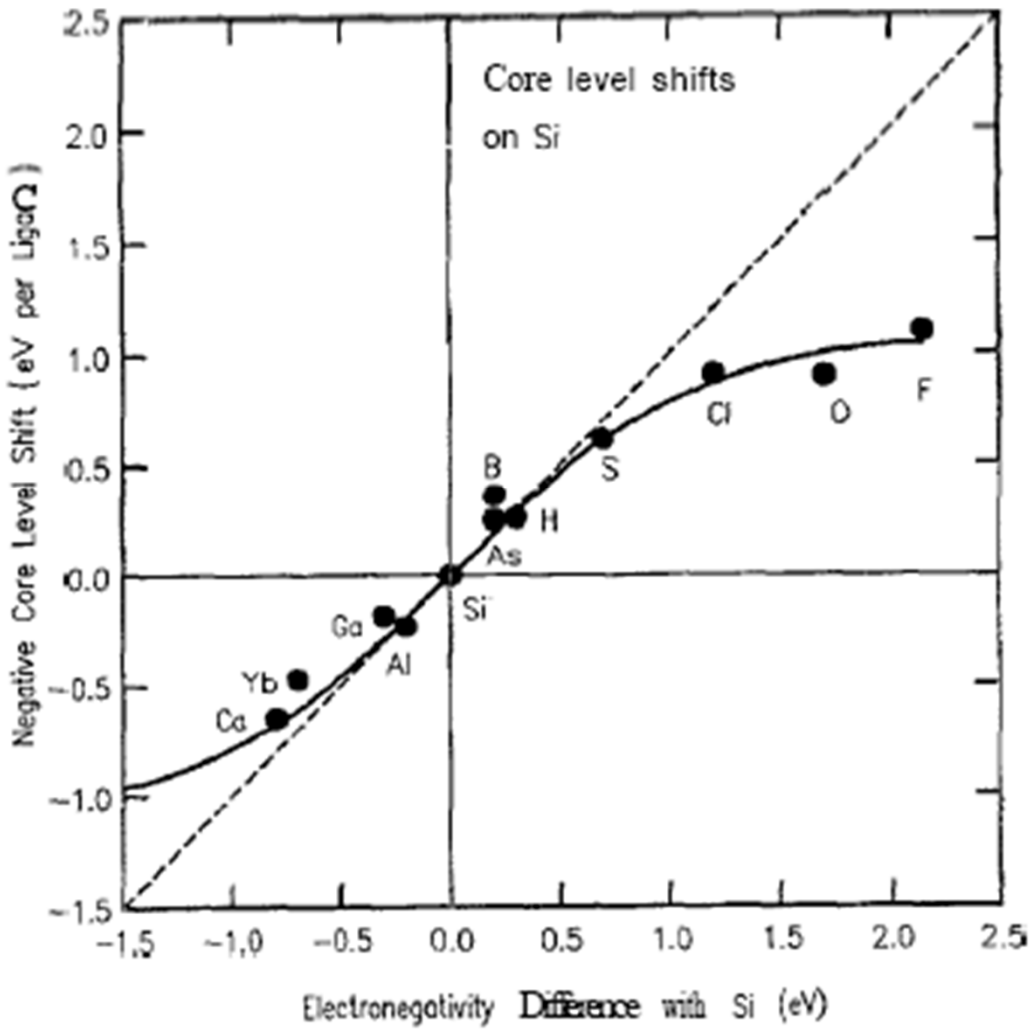
Van der Laan et al., Phys. Rev. B 23 (1981) 4369

Chemical shift

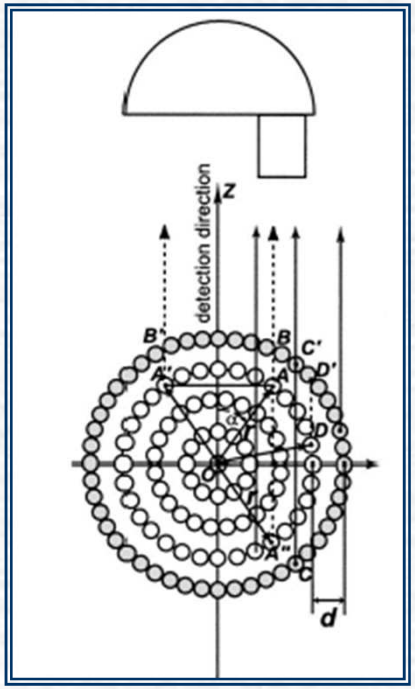


C 1s 285-300 eV
O 1s 530-540 eV
C 1s CO_2 298 eV
C 1s CH_4 291 eV

Chemical shift vs.electronegativity



Sensitivity to the local environmentin free clusters



J. Chem. Phys.,
Vol. 120, No. 1, 1
January 2004

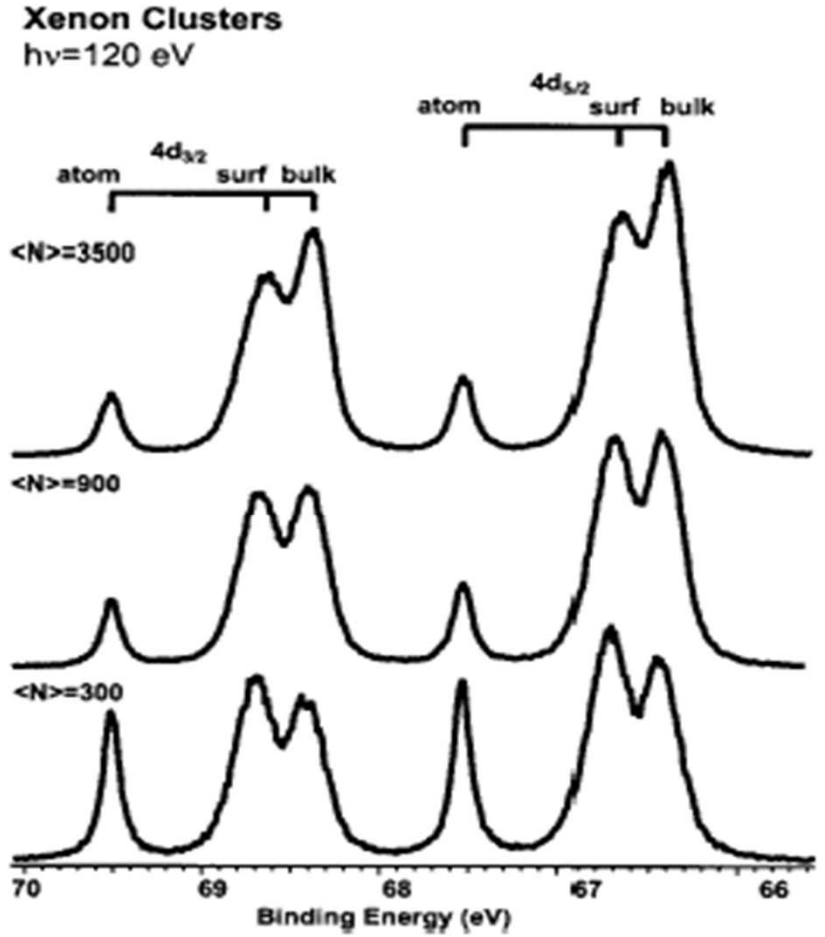
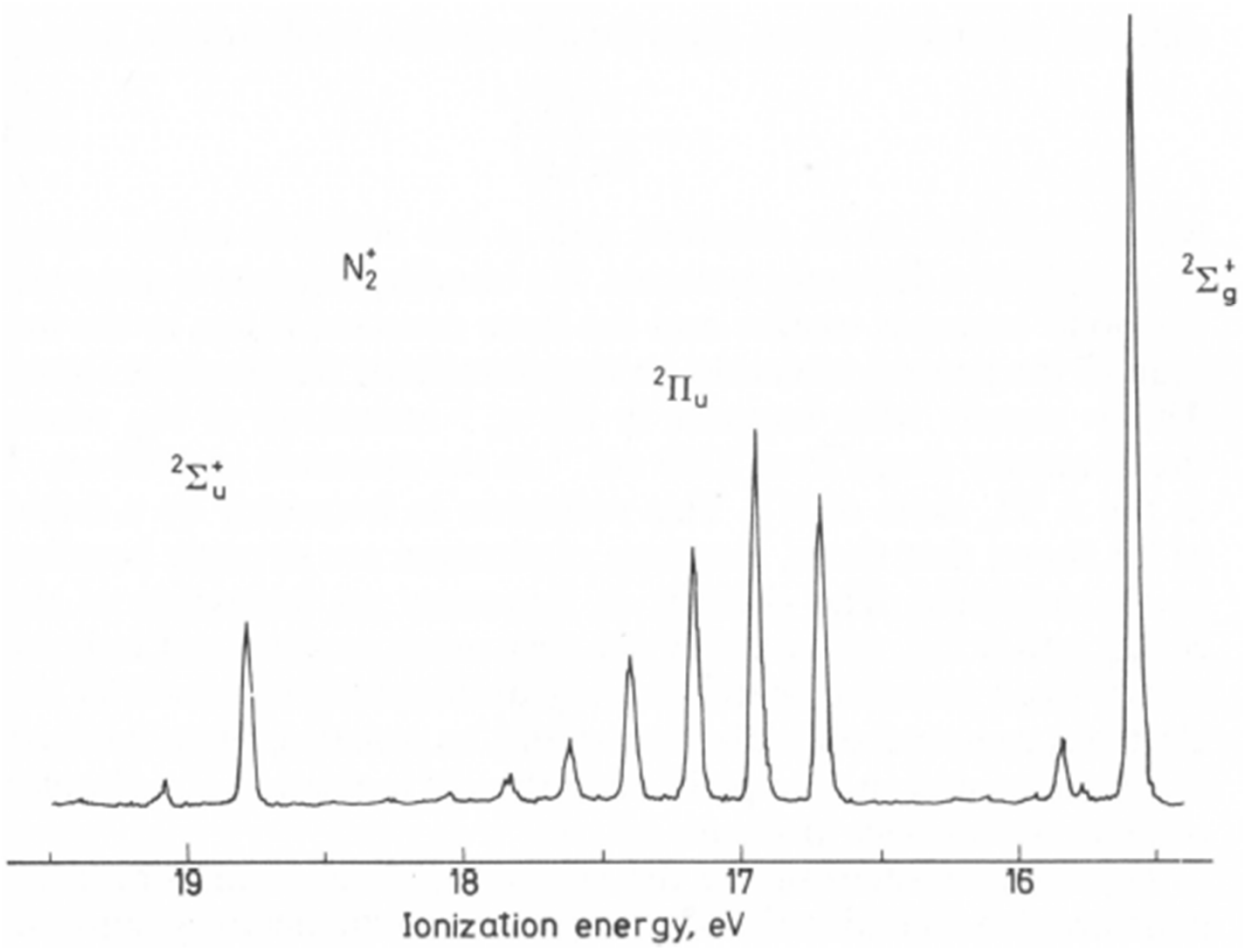


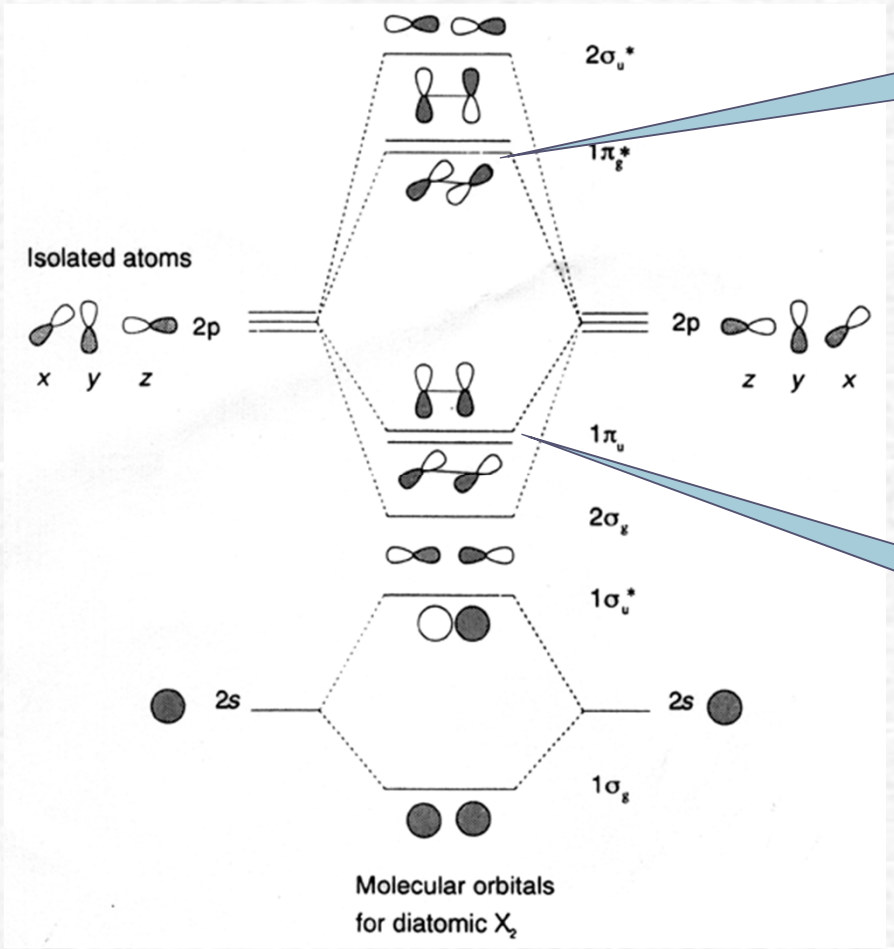
FIG. 3. 4*d* XPS spectra of xenon clusters of three mean sizes at 120 eV photon energy: $\langle N \rangle \approx 300$, 900, and 3500.

Tchaplyguine et al.

PES spectrum of N_2



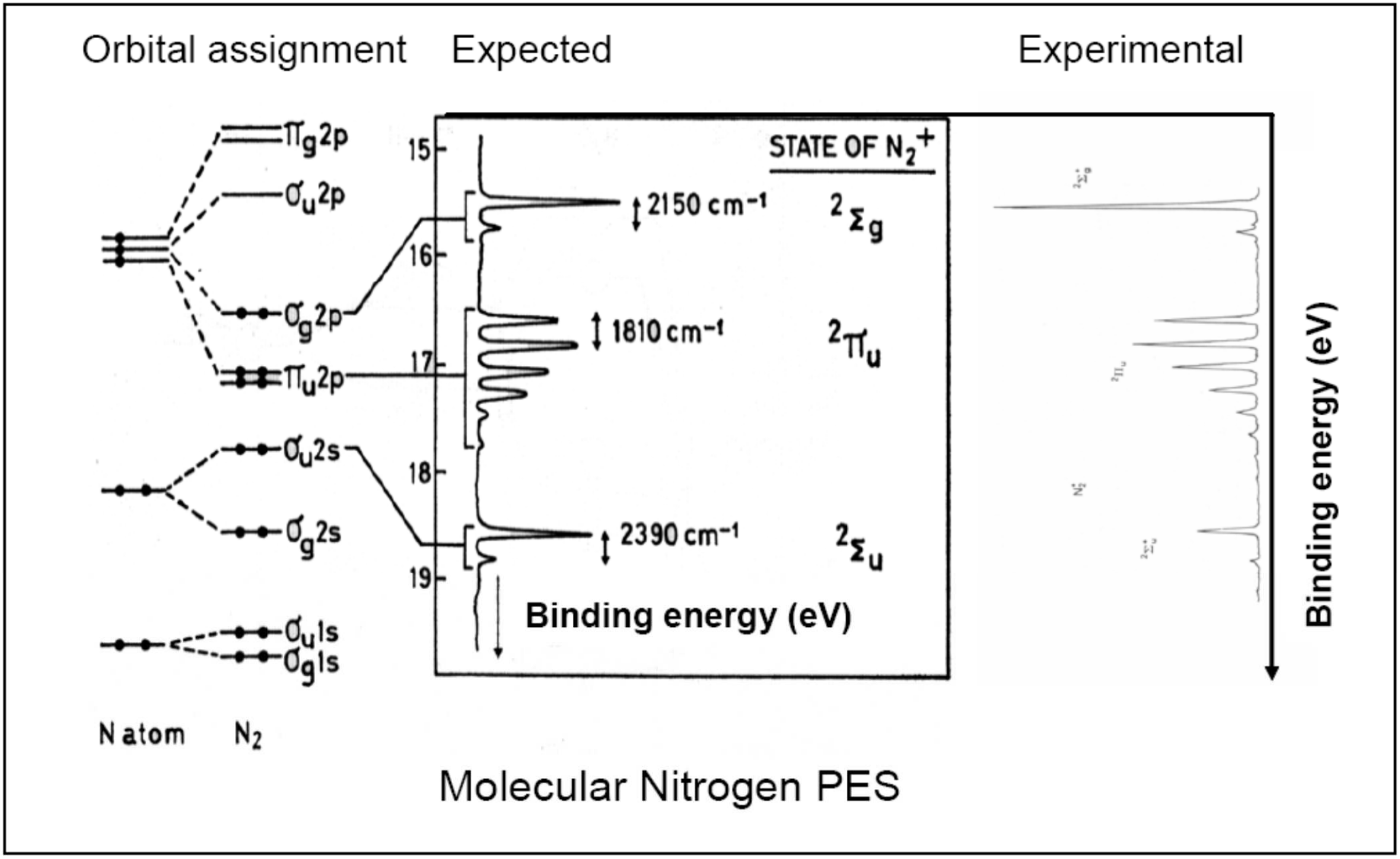
Diatomic molecule e levels



LUMO

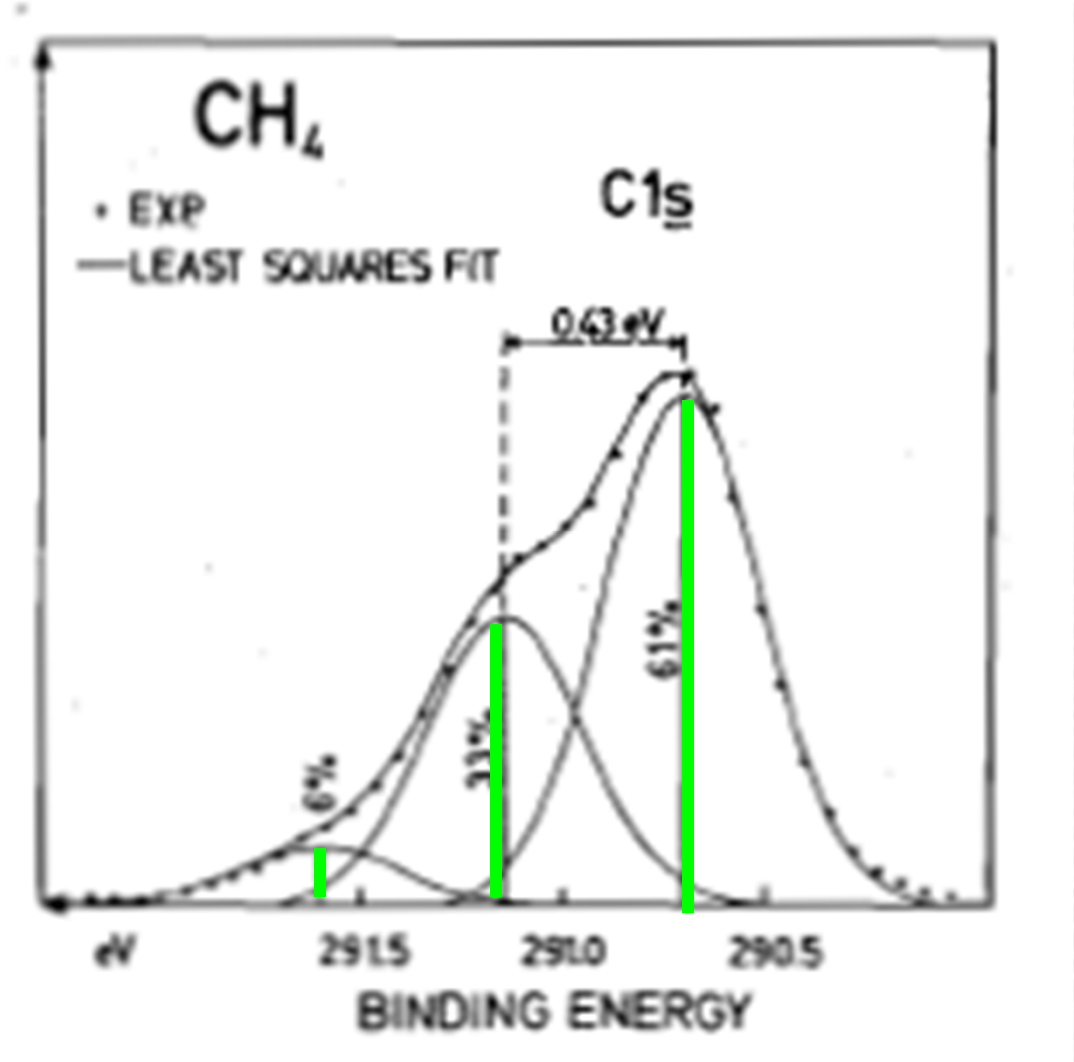
HOMO

Experimental PE spectrum of N_2, and MOs



Molecular Nitrogen PES

Core PE vibrational spectrum



K. Siegbahn et al “ESCA Applied to free molecules”

Molecular PE x-section

$$H_0 = H_0(kin) + H_0(e-n) + H_0(e-e) + H_0(s-o) + H_0(n-n) =$$

$$= \sum_1^N \frac{p_i^2}{2m} + \sum_1^N -\frac{Ze^2}{r_i} + \sum_{i>j}^N \frac{e^2}{r_{ij}} + \sum_1^N \zeta(r_j)\vec{l}_i \bullet \vec{s}_i + \sum_{i>j}^M \frac{e^2 Z_i Z_j}{r_{ij}}$$

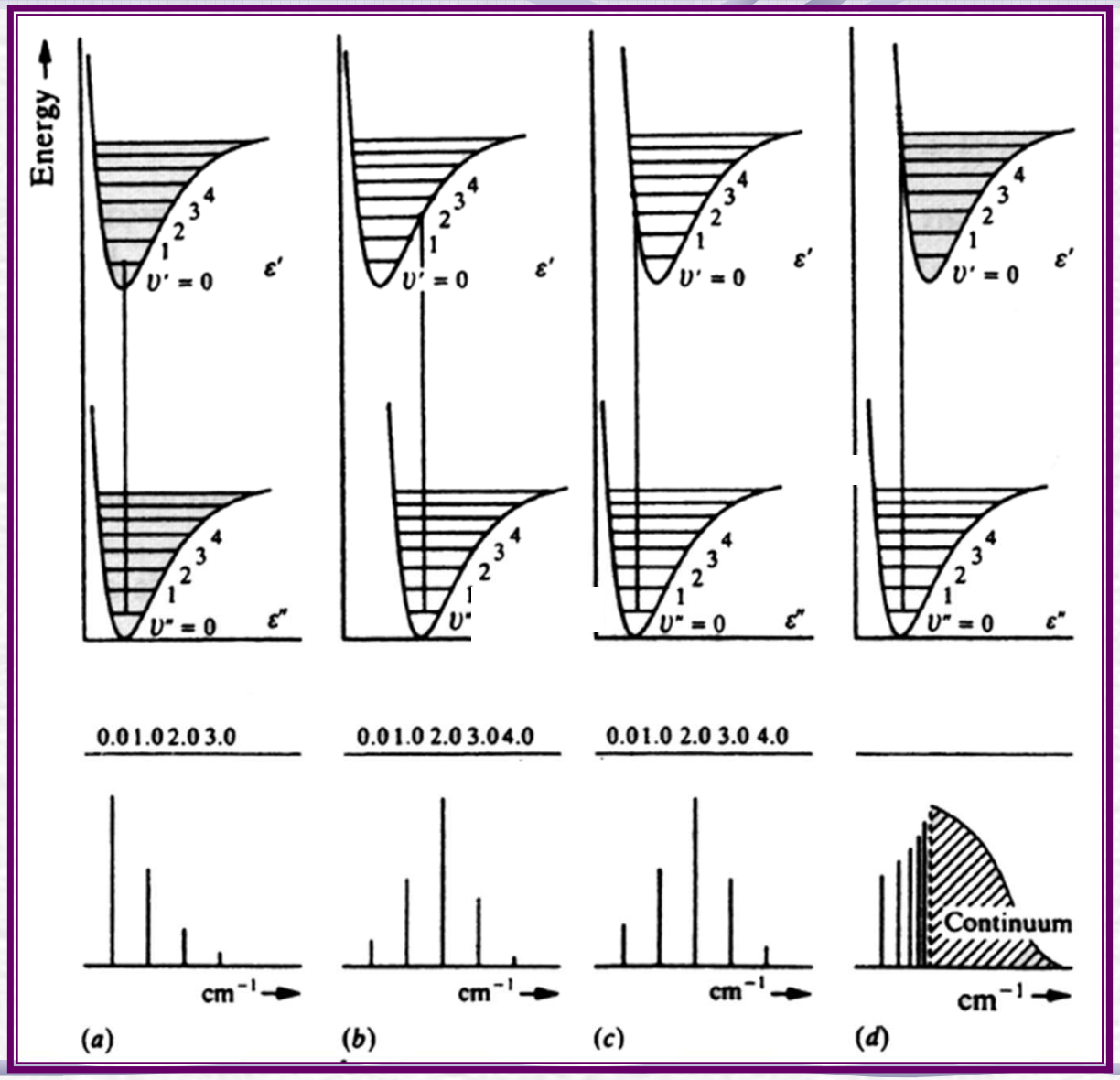
Born Oppenheimer

$$\left|\Psi_{A,B}^{(N)}\right\rangle = \left|\Psi_{A,B}^{(N)}\right\rangle \left|\Psi_{A,B}^{vib}\right\rangle$$

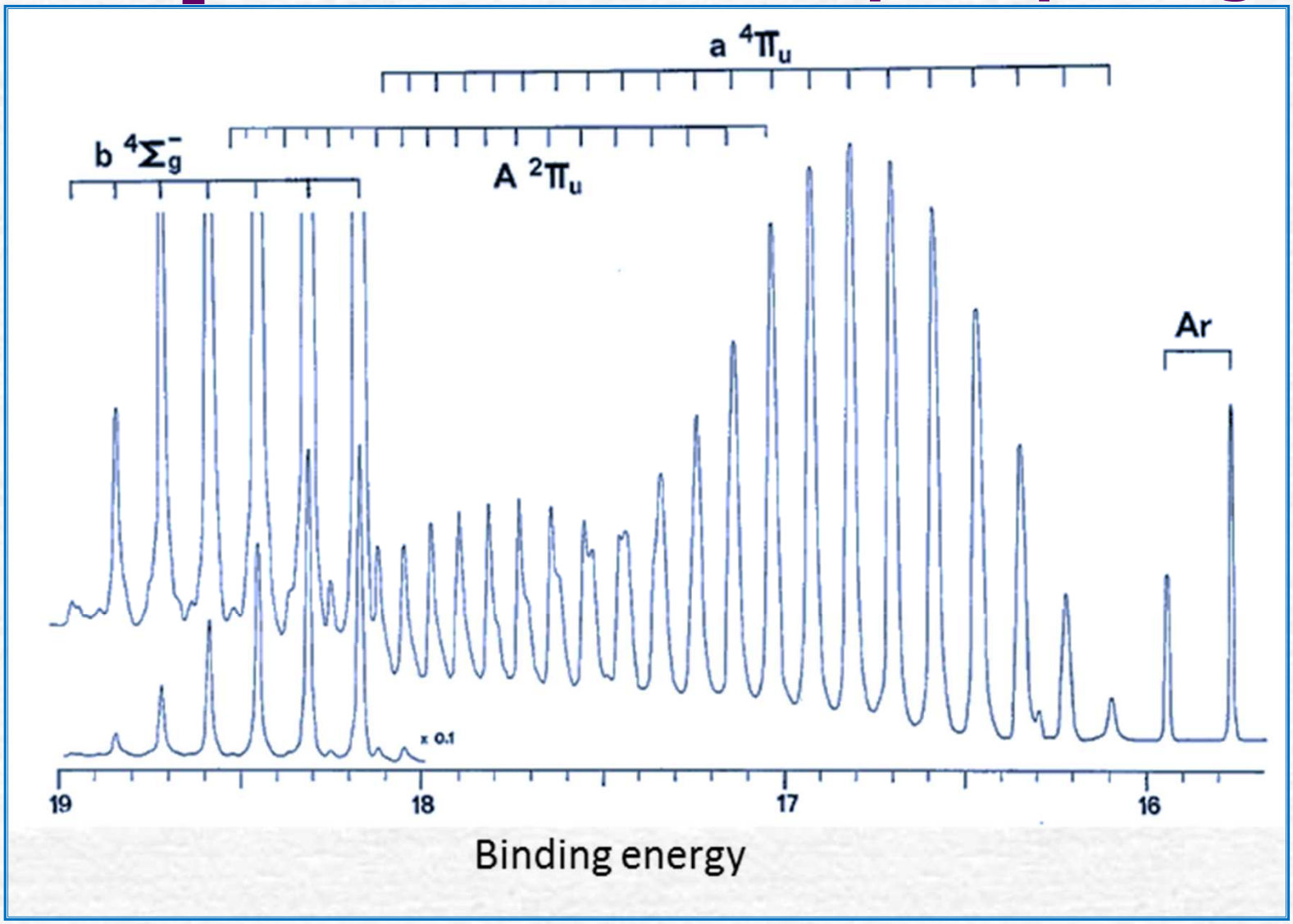
$$\frac{d\sigma}{d\Omega dE_e} \propto \frac{1}{h\nu} \sum_{A,B} \left| \hat{\varepsilon} \bullet \left\langle \varepsilon_l \left| \vec{r}_j \right| \sum_{A\lambda} C_{A\lambda} \phi_{A\lambda} \right\rangle \left\langle \Psi_B^{(N-1)} \left| \Psi_R^{(N-1)} \right\rangle \right|^2$$

$$\left| \left\langle \Psi_B^{vib} \left| \Psi_A^{vib} \right\rangle \right|^2 \delta(E_e + E_B^{(N-1)} - E_A - h\nu)$$

Frank Condon Factors

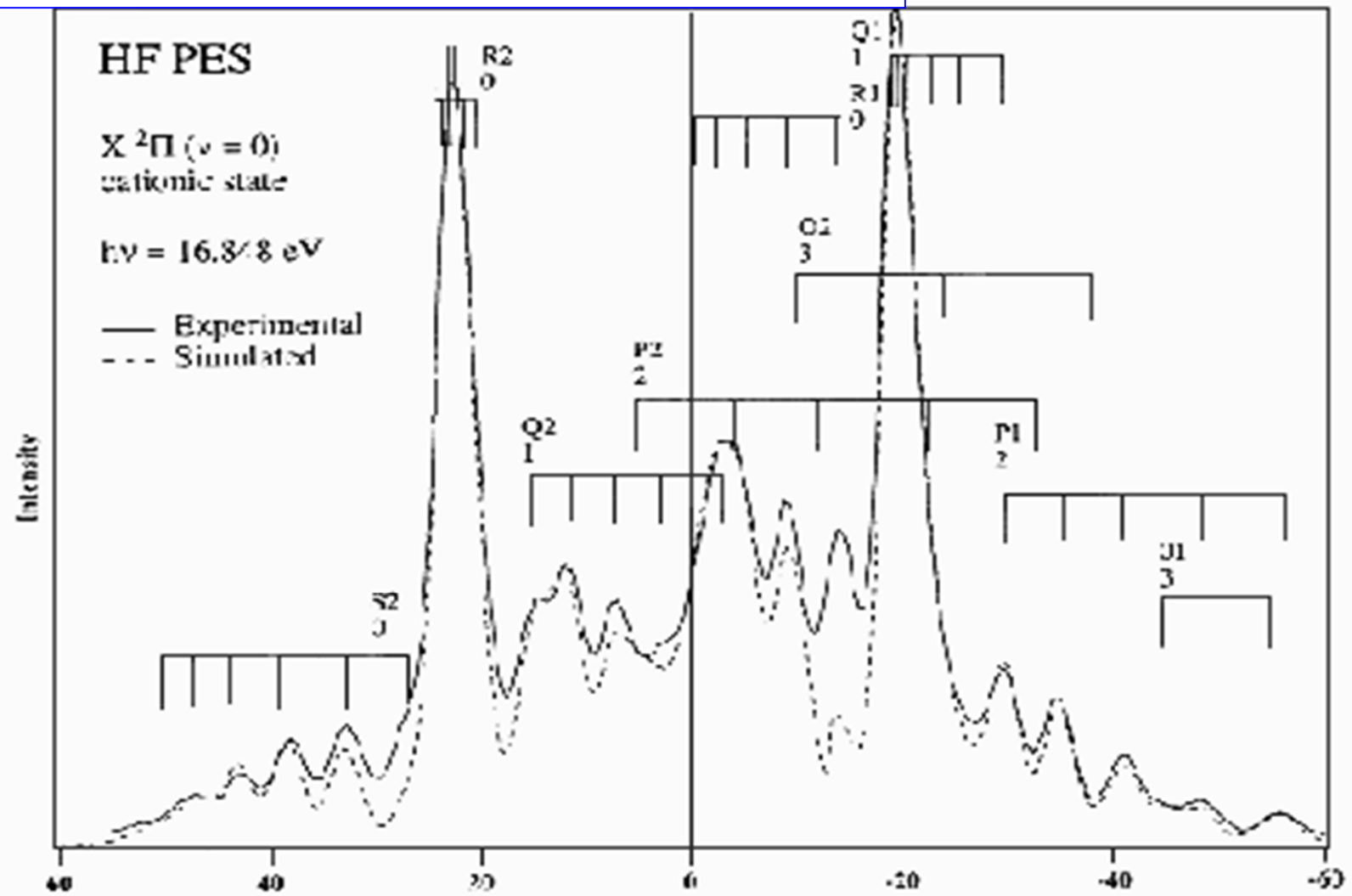


PE O_2 vibrational and multiplet splitting

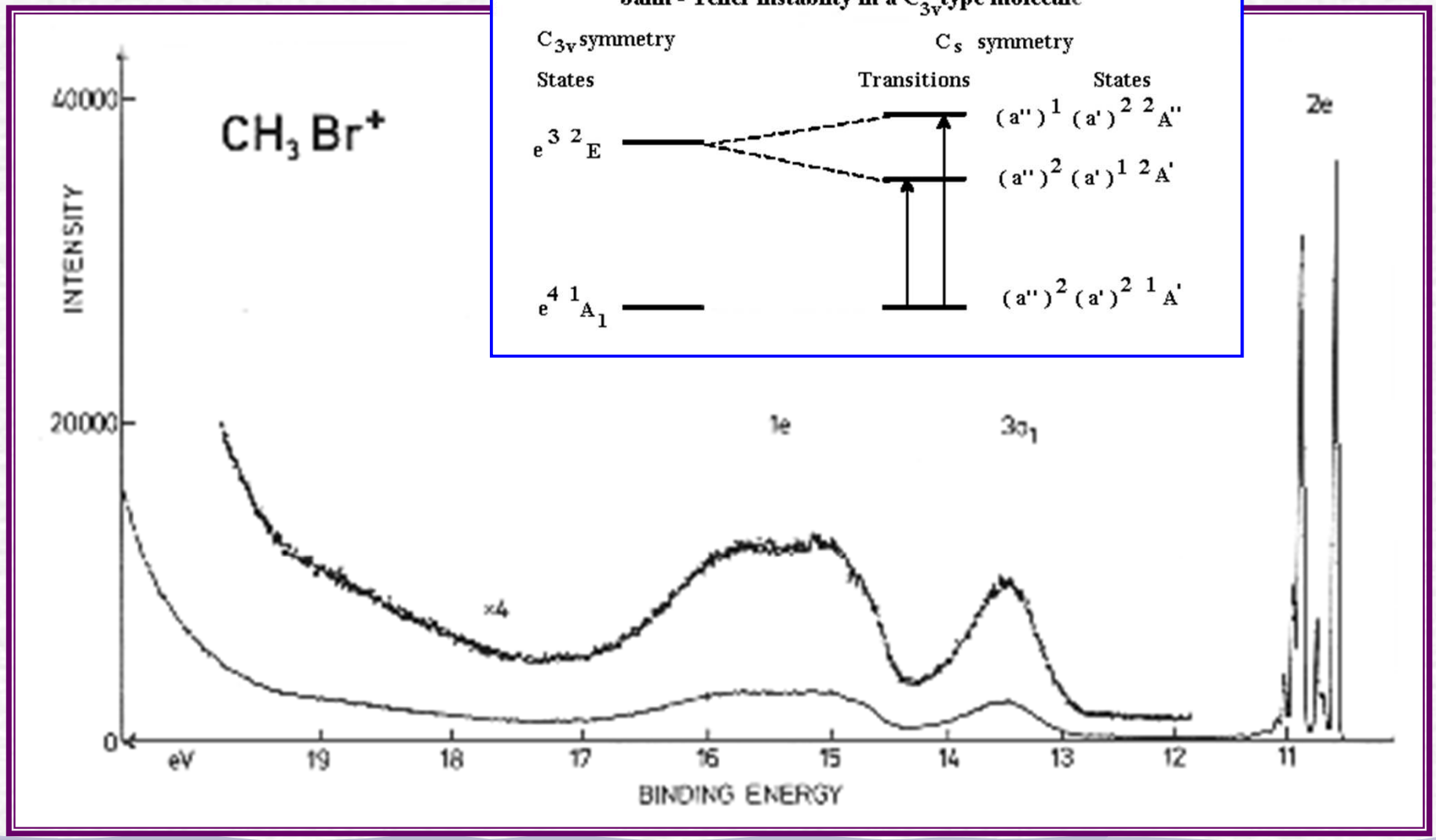


Rotational structure HF

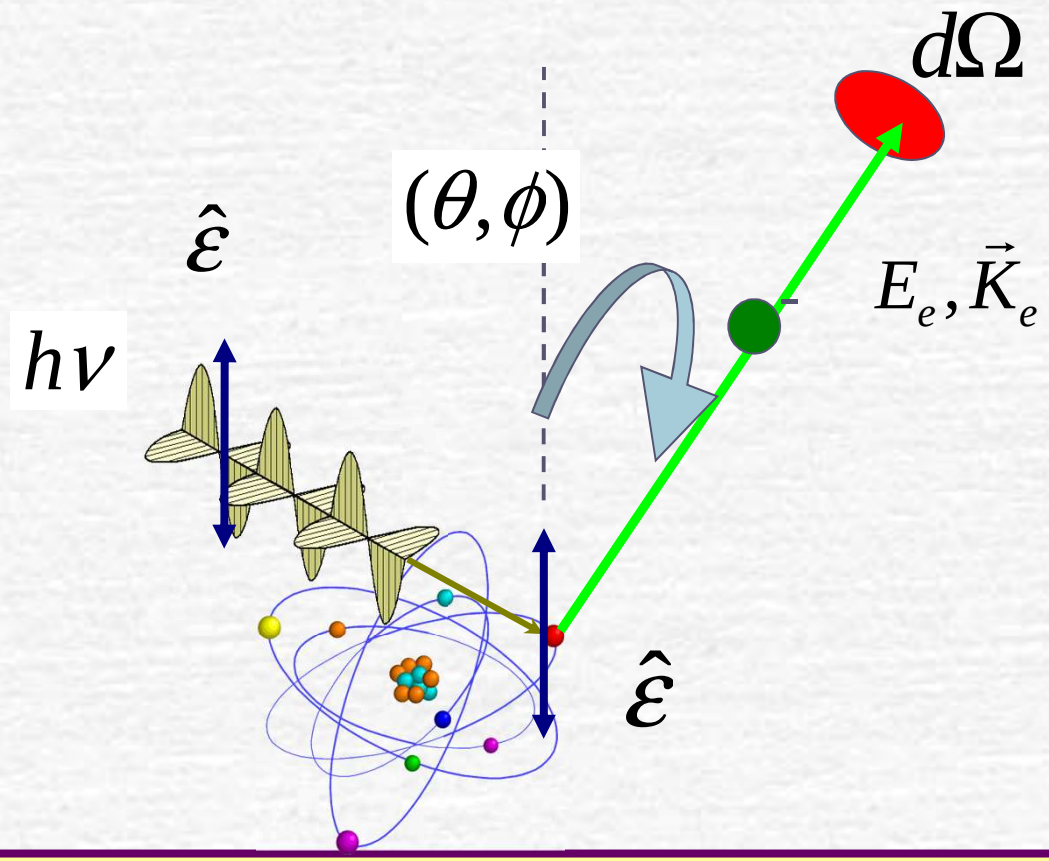
1 and 2 refer to the $^2\Pi_{3/2}$ and $^2\Pi_{1/2}$ spin-orbit split components



Jahn Teller splitting

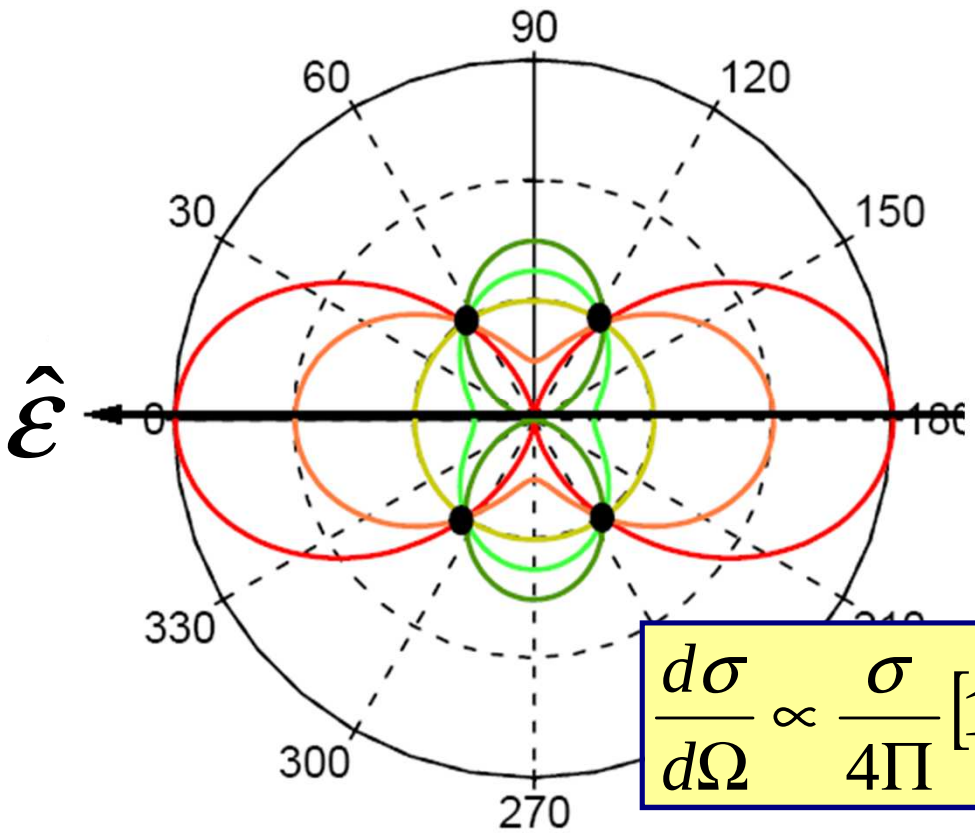


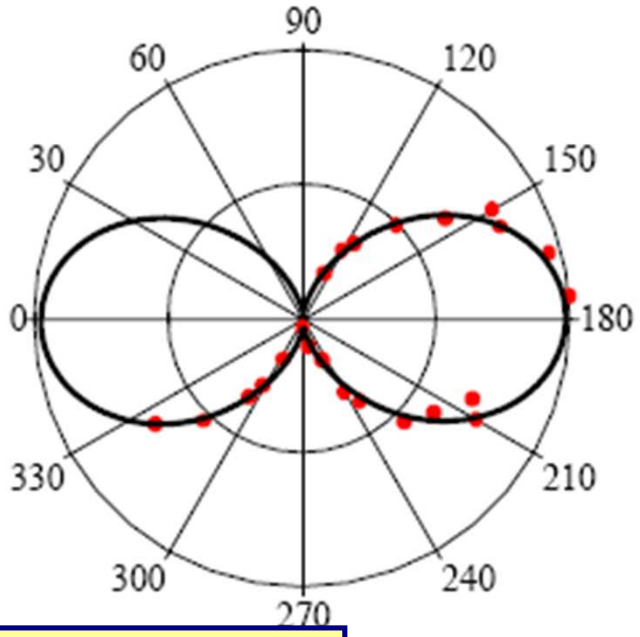
PE angular distribution



$$\frac{d\sigma}{d\Omega} \propto \frac{1}{h\nu}\sum_{A,B}\left|\hat{\varepsilon}\bullet\left\langle\varepsilon_l\left|\vec{r}_j\right|\phi_j(\vec{r}_j,\sigma_j)\right\rangle\left\langle\Psi_B^{(N-1)}\left|\Psi_R^{(N-1)}\right\rangle\right|^2$$

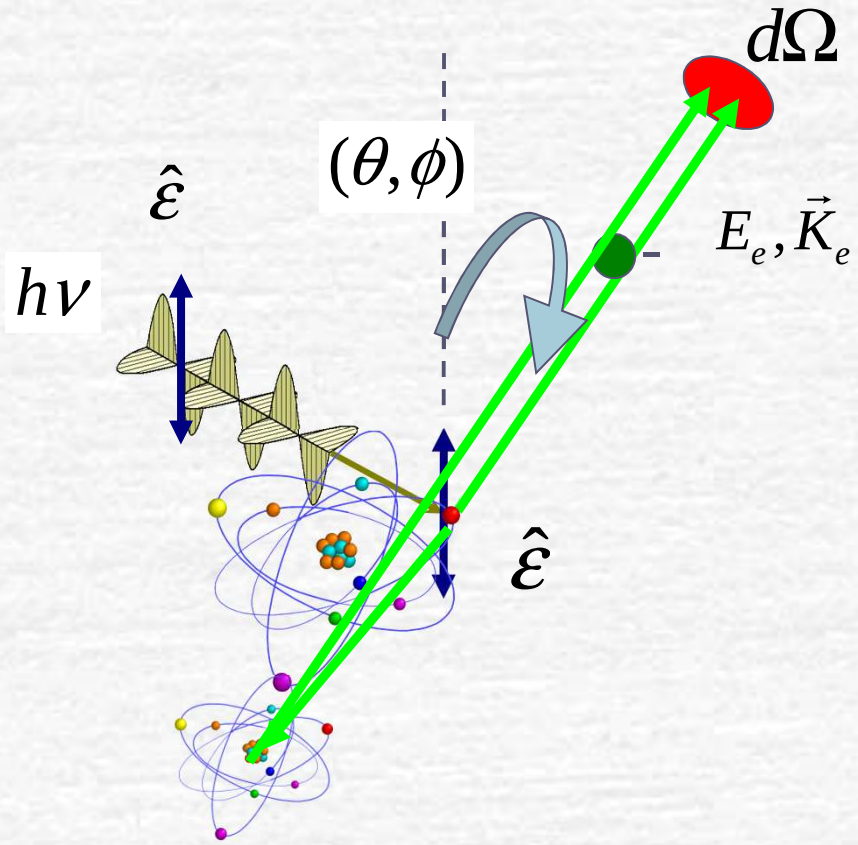
Angular distributions





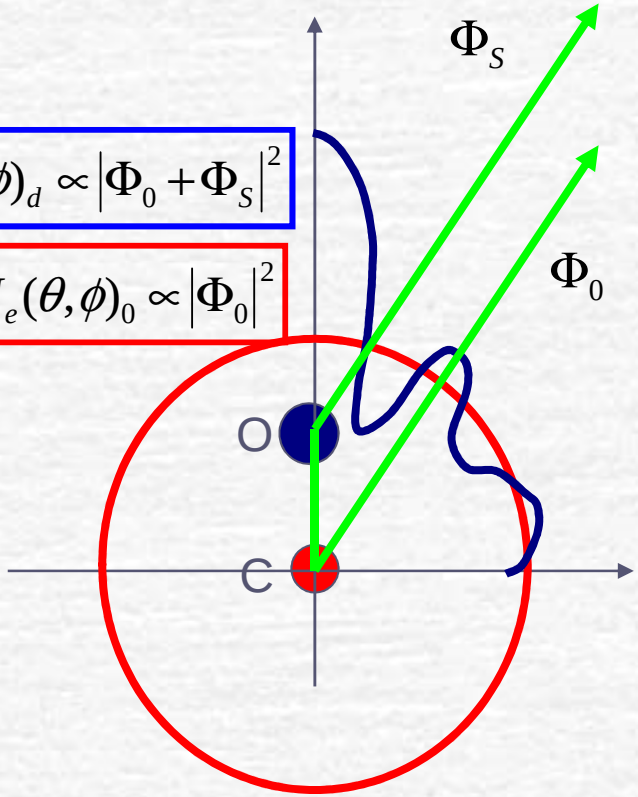
$$\frac{d\sigma}{d\Omega} \propto \frac{\sigma}{4\Pi}\left[1+\beta P_2 \cos(\vartheta)\right]$$

$$J_e \left| \Phi_{direct} + \sum_i \Phi^i_{scattered} \right|^2$$

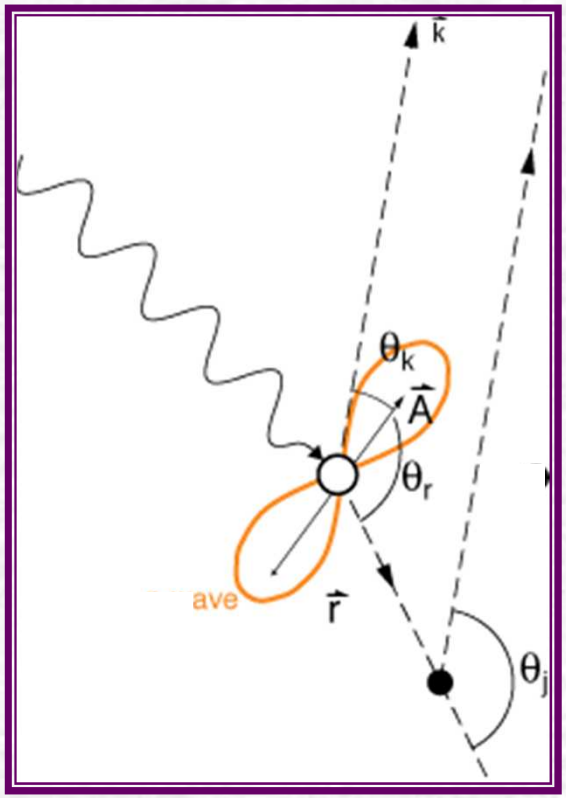


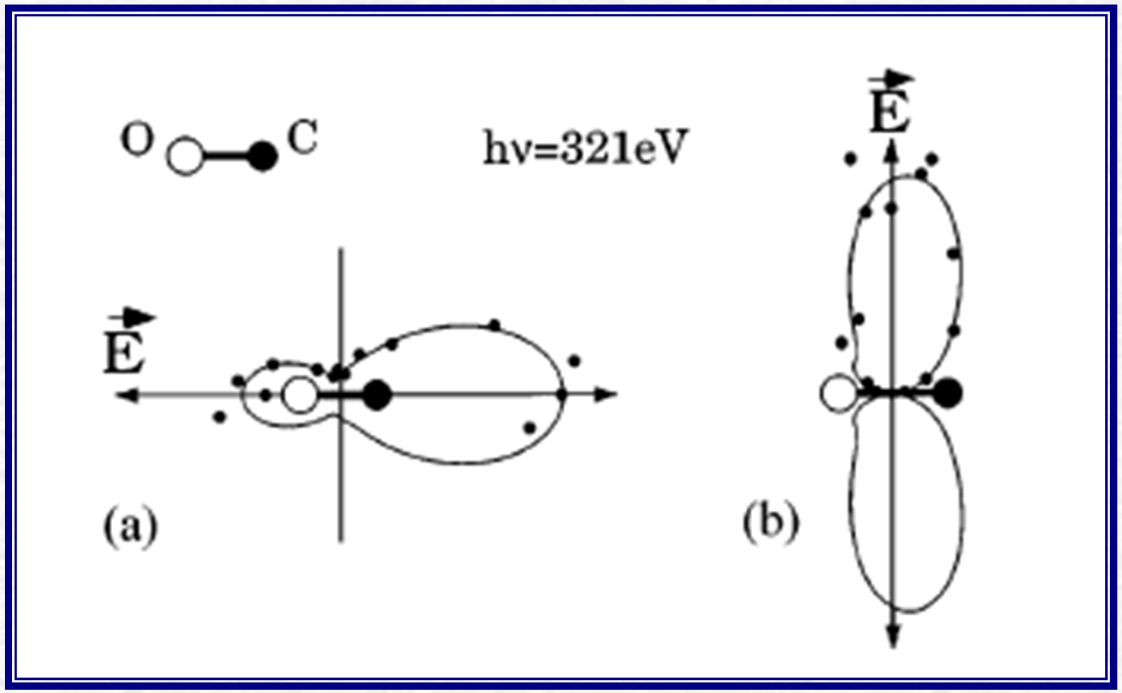
$$J_e(\theta,\phi)_d \propto \left|\Phi_0 + \Phi_S\right|^2$$

$$J_e(\theta,\phi)_0 \propto \left|\Phi_0\right|^2$$



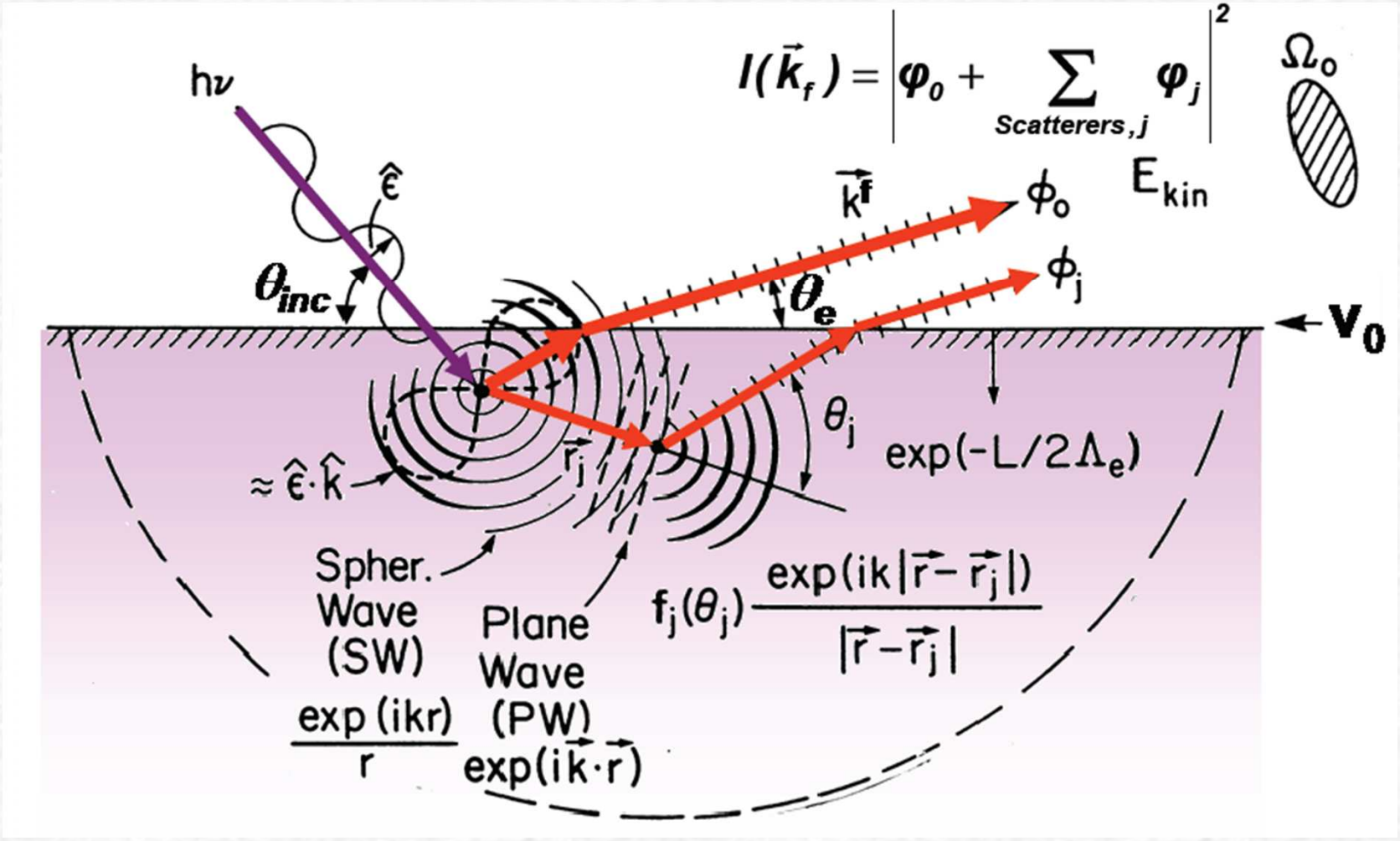
Fixed in space molecules
CO C 1s



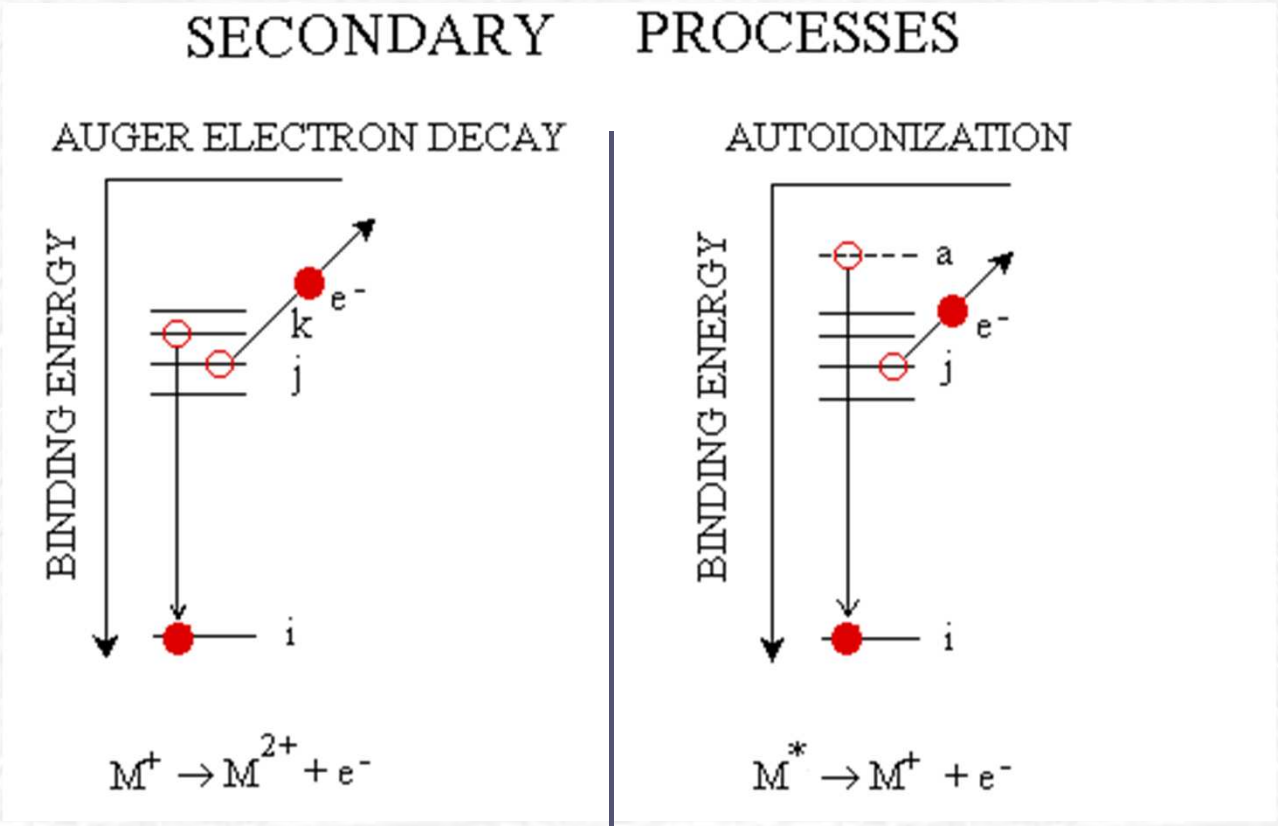


F. Heiser et al. VOLUME 79, NUMBER 13 PHYSICAL REVIEW LETTERS

Application to surfaces



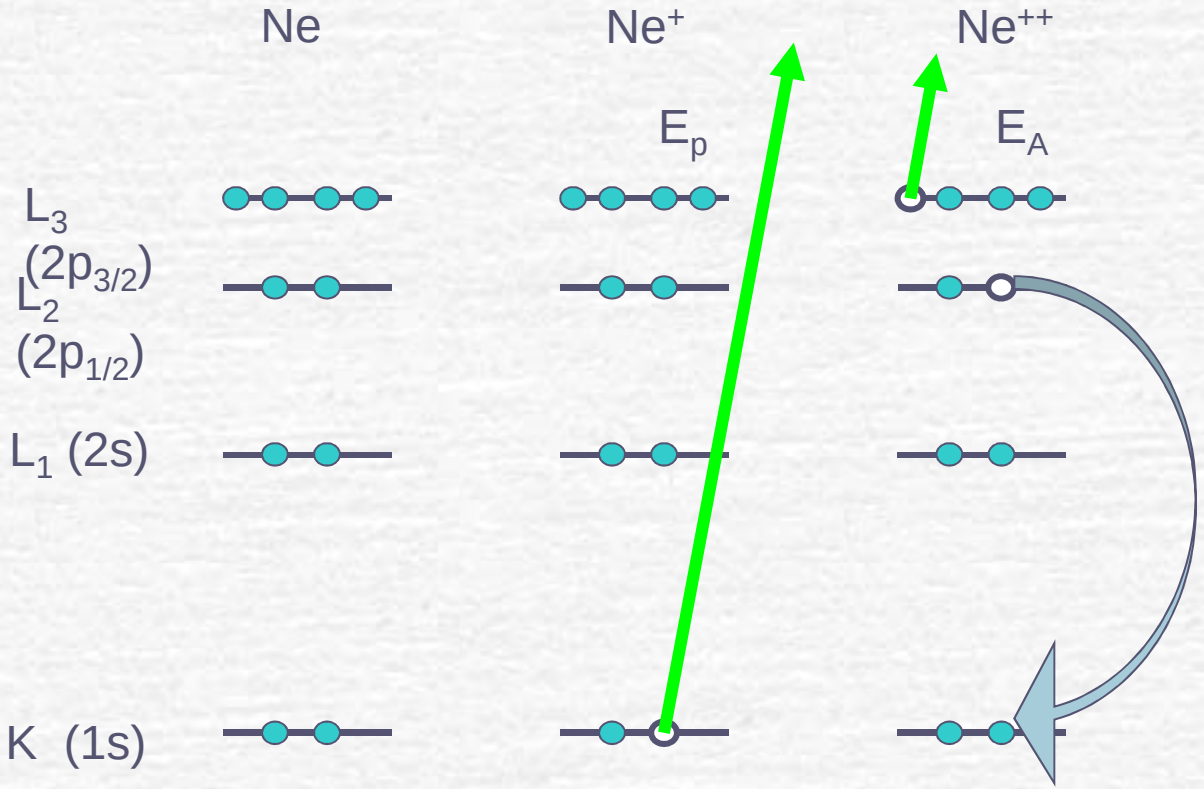
Core hole relaxation



Global energy, angular Momentum and parity

Energy, angular momentum, Dipole selections at each step

Auger decay



Auger Transition	Double ion valence configuration	Multiplet Terms
KL_1L_1	$2s^0\ 2p^6$	$^1S_0$
$KL_1L_{2,3}$	$2s^1\ 2p^5$	$^1P_1,\ ^3P_0,\ ^3P_2,\ ^3P_1$
$KL_{2,3}L_{2,3}$	$2s^2\ 2p^4$	$^1S_0,\ ^3P_0,\ ^3P_2,\ ^1D_2$

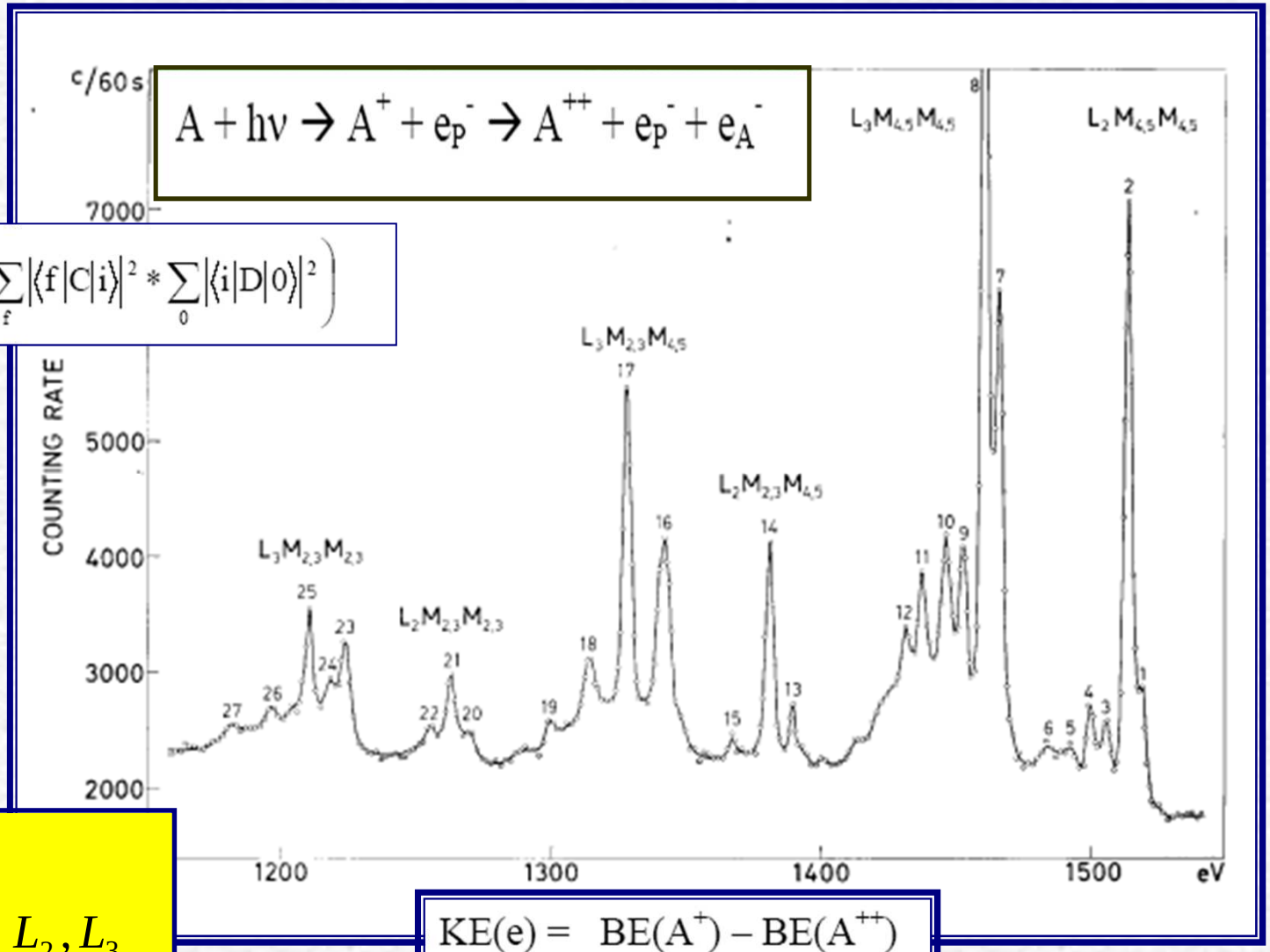
$$EA(KL_1L_2) = E(K) - E(L_1) - E(L_2, L_1)$$

Kr Auger spectrum

K. Siegbahn et al
"ESCA Applied
to free molecules"

$$A + h\nu \rightarrow A^{+} + e_p^{-} \rightarrow A^{++} + e_p^{-} + e_A^{-}$$

$$P \propto \sum_i \left(\sum_f \left| \langle f | C | i \rangle \right|^2 * \sum_0 \left| \langle i | D | 0 \rangle \right|^2 \right)$$



$$|0\rangle \rightarrow Kr^{I}$$

$$|i\rangle \rightarrow Kr^{II} \rightarrow L_2, L_3$$

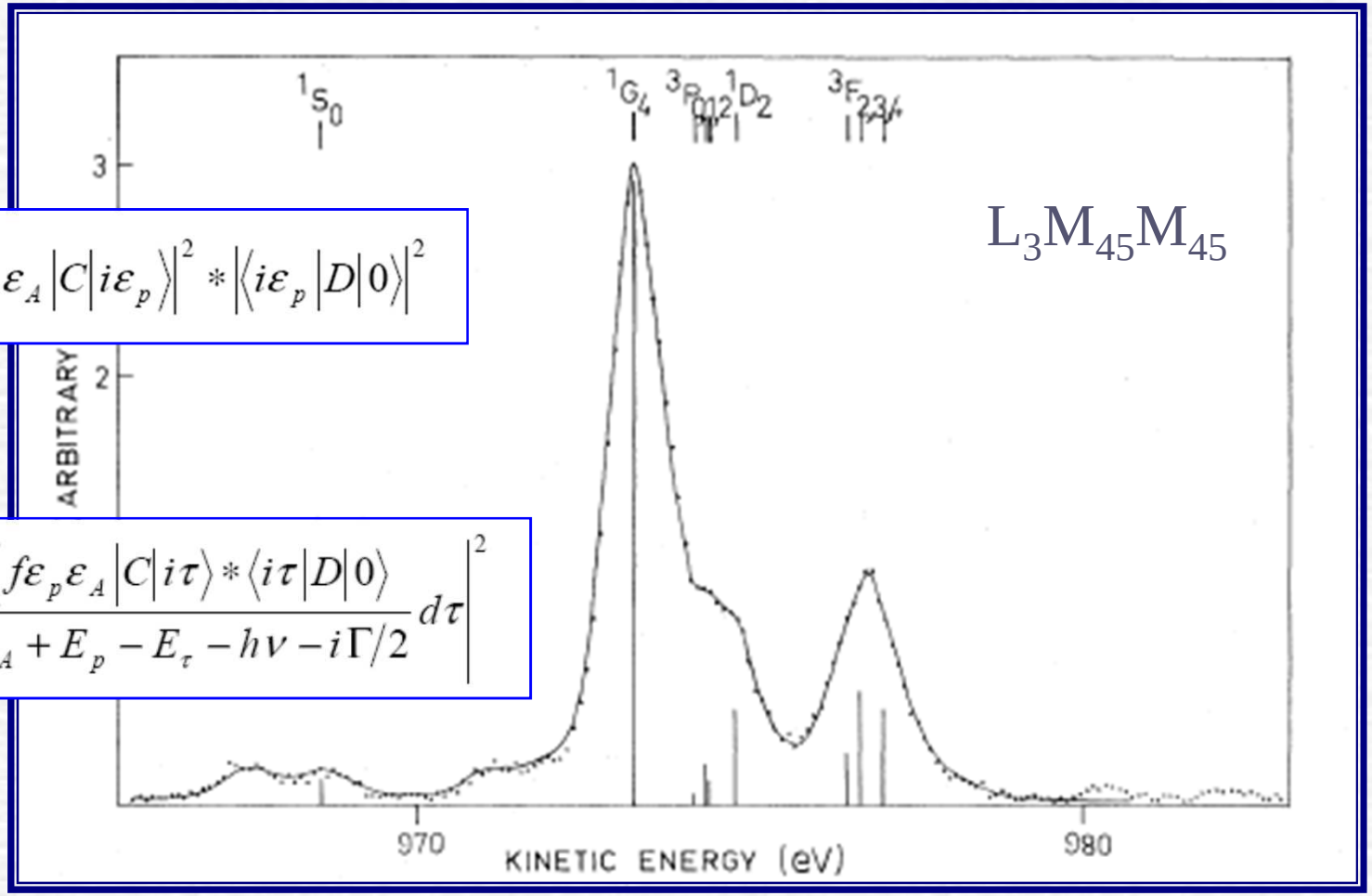
$$|f\rangle \rightarrow Kr^{III} \rightarrow M_i M_j$$

$$KE(e) = BE(A^{+}) - BE(A^{++})$$

Zn Auger multiplet splitting

$$P(0,i,f) \propto \left| \left\langle f\varepsilon_p\varepsilon_A \middle| C \middle| i\varepsilon_p \right\rangle \right|^2 * \left| \left\langle i\varepsilon_p \middle| D \middle| 0 \right\rangle \right|^2$$

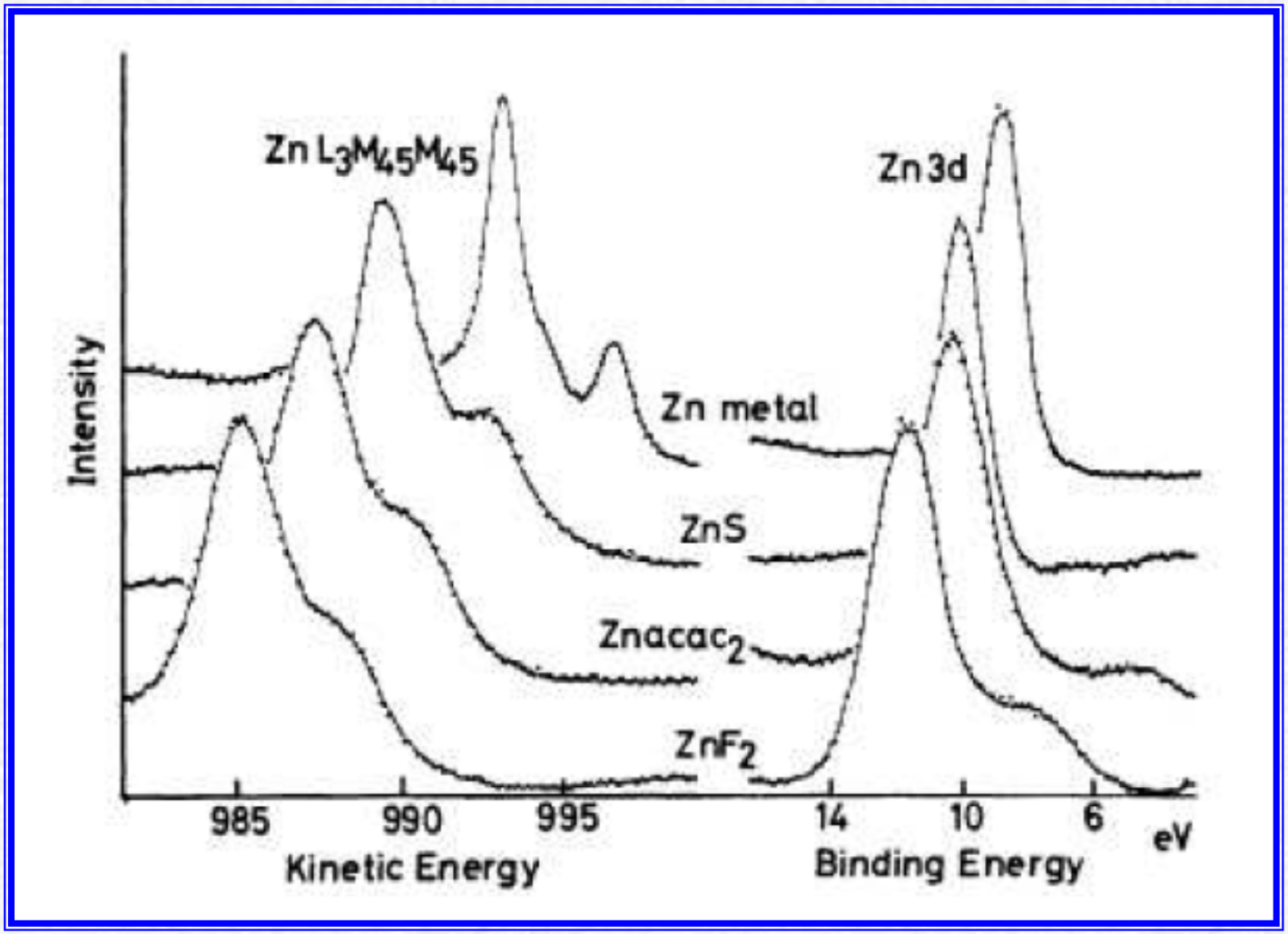
$$P(0,i,f) \propto \left| \int \frac{\left\langle f\varepsilon_p\varepsilon_A \middle| C \middle| i\tau \right\rangle * \left\langle i\tau \middle| D \middle| 0 \right\rangle}{E_A + E_p - E_\tau - h\nu - i\Gamma/2} d\tau \right|^2$$



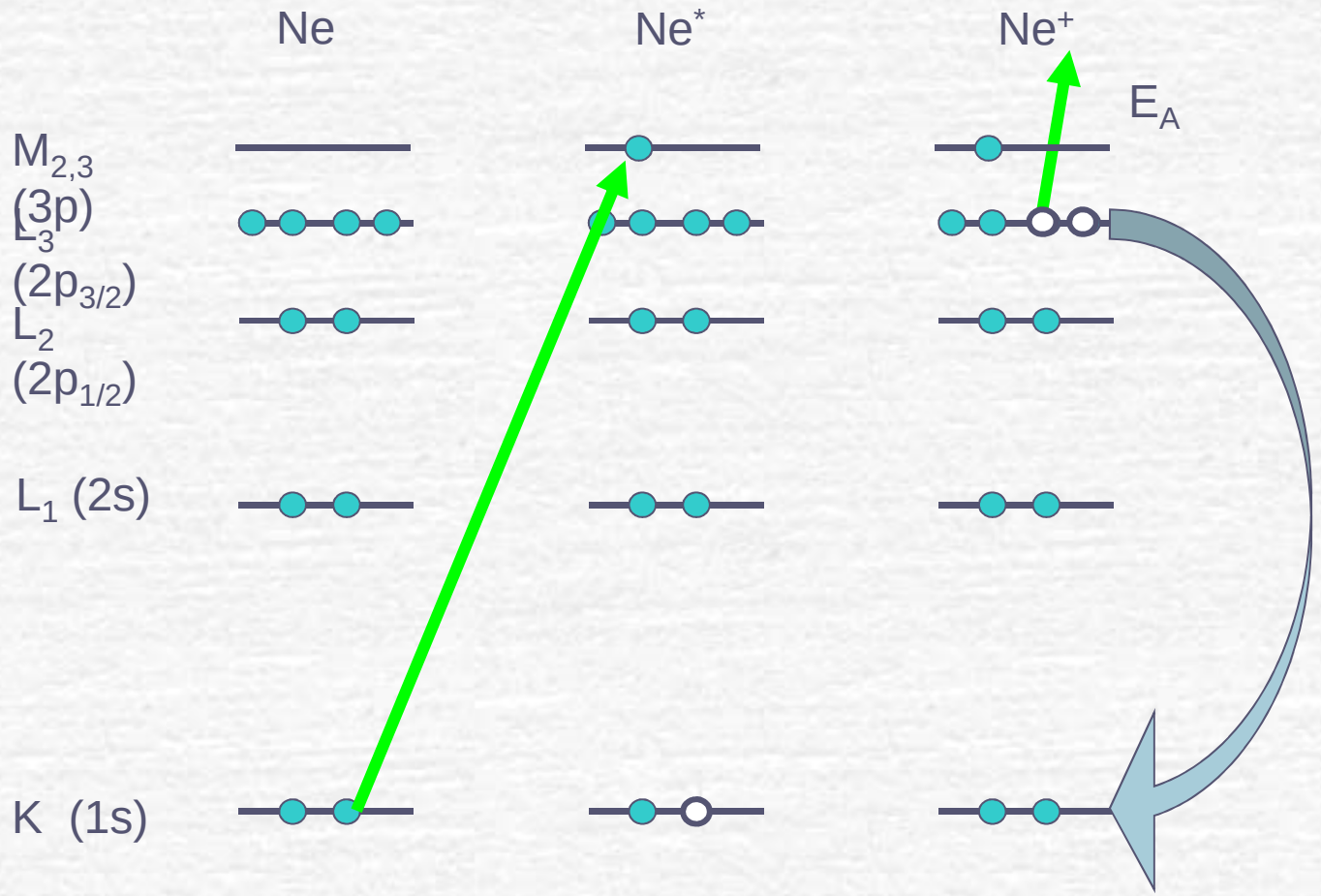
$L_3M_{45}M_{45}$

Aksela et al. PRL 33,999 (1974)

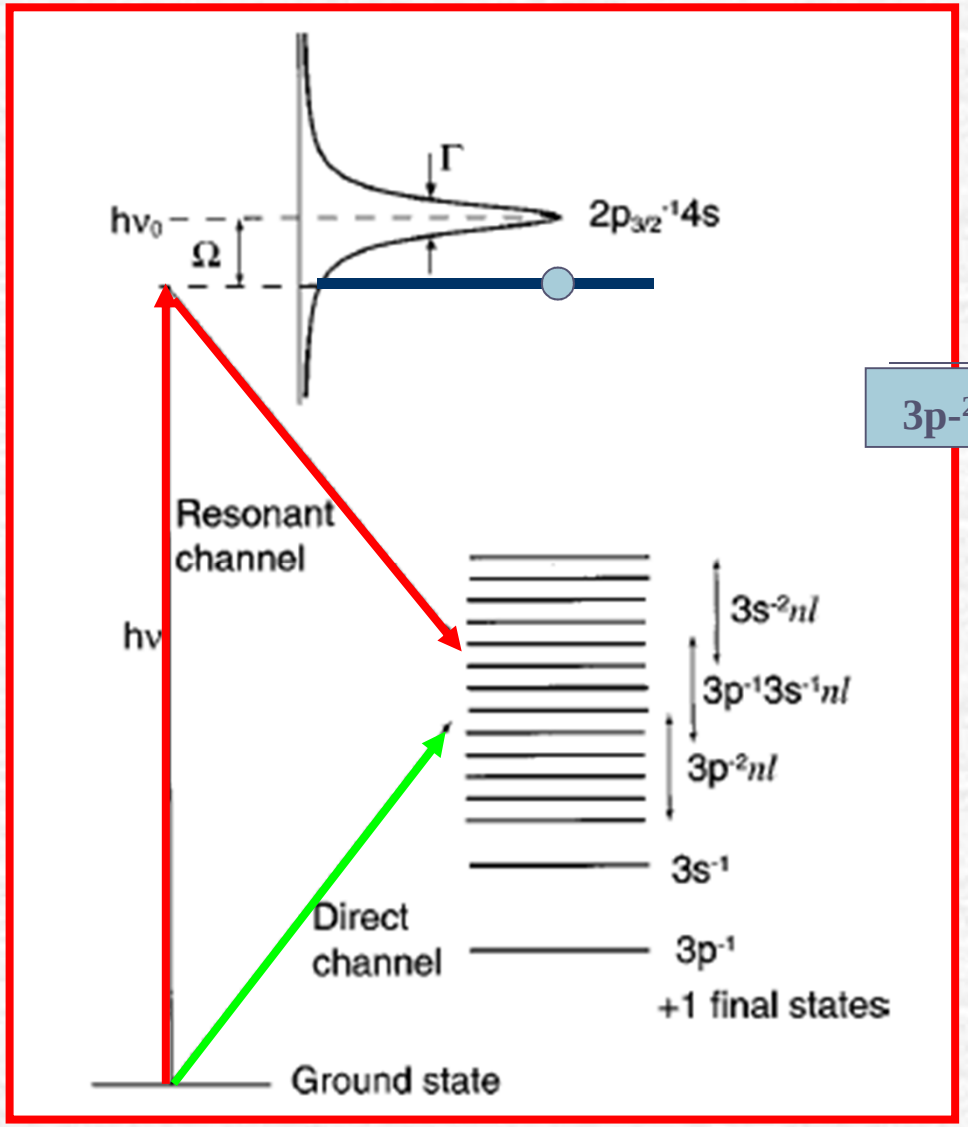
Auger chemical shift



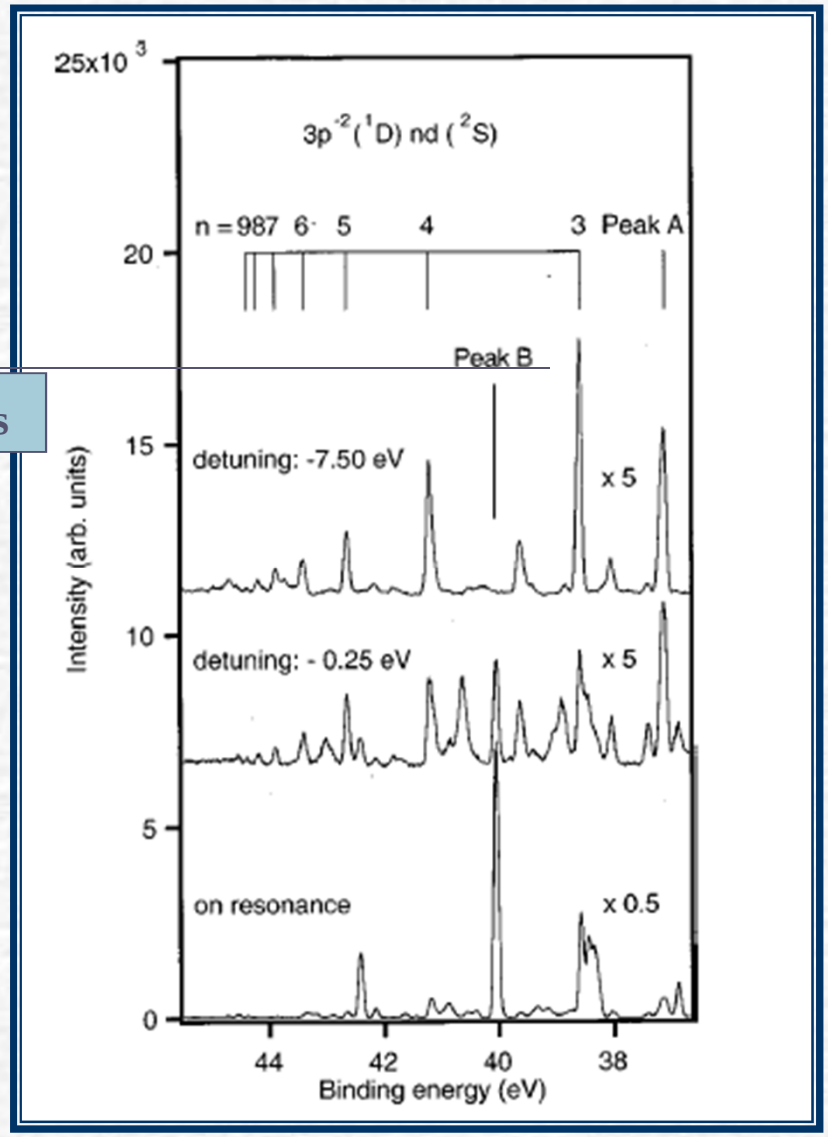
Autoionizing decay



Ar Autoionization spectrum



3p-2 5s



Phys. Rev. A 63,032514

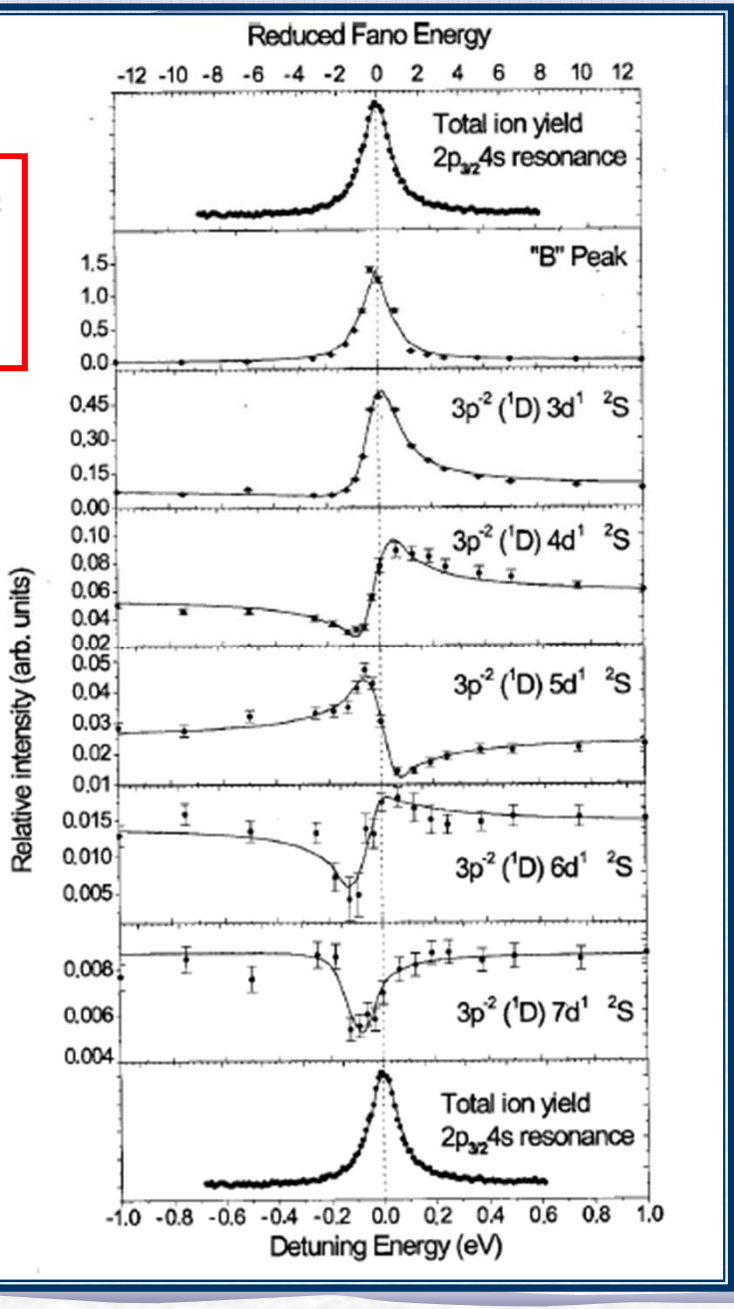
Quantum interference

$$P(0,i,f)=\left|\int \frac{\langle f\varepsilon_A|C|i\tau\rangle * \langle i\tau|D|0\rangle}{E_A+E_p-E_\tau-h\nu-i\Gamma/2}d\tau+\langle f\varepsilon_A|D|0\rangle\right|^2$$

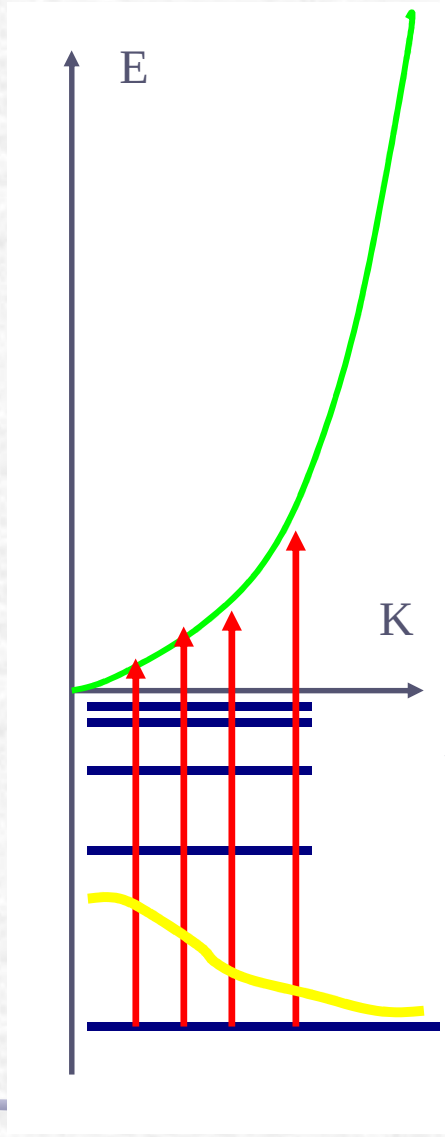
$$\sigma(h\nu)=\sigma_T\left\{\rho'^2\left[\frac{(q+\varepsilon')^2}{\varepsilon'^2+1}+\frac{\Delta h\nu}{\Gamma}-1\right]+1\right\}.$$

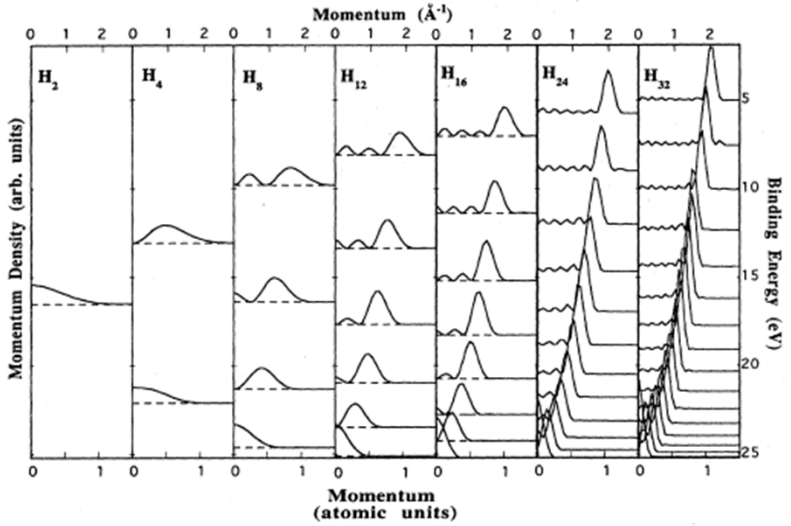
What does it happen when the photoemission line
concides with the autoionization line?
Interference between direct and resonant channel

Phys. Rev. A 63,032514



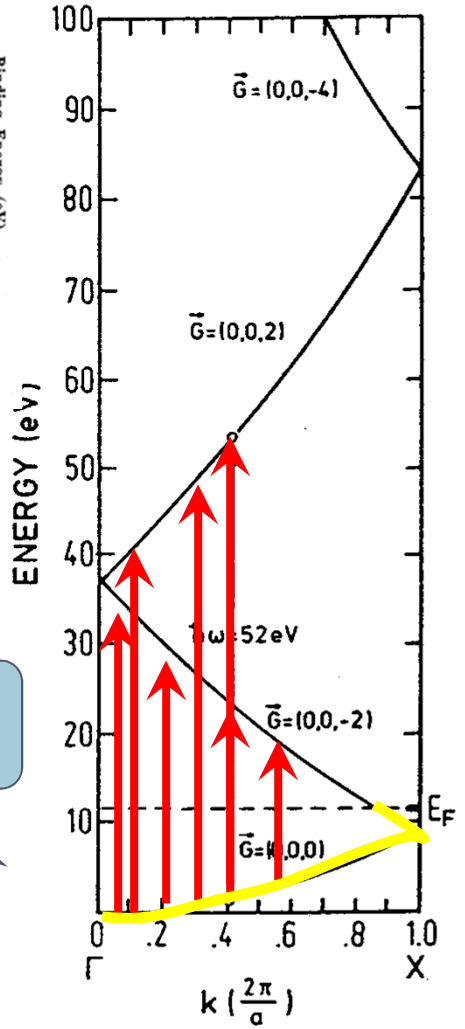
From central to periodic potential





$$\left\langle \varepsilon_l \middle| \vec{r}_j \middle| \phi_j(\vec{r}_j,\sigma_j) \right\rangle \left\langle \Psi_B^{(N-1)} \middle| \Psi_R^{(N-1)} \right\rangle$$

$$\left\langle \varepsilon_l \middle| \vec{r}_j \middle| \phi_j(\vec{r}_j,\sigma_j) \right\rangle A(\vec{k},E)$$



Spectral Function in Interacting Solids

$$\Psi_{Nf} = A\,\Psi^{N-1}_{f}\,\Phi_{kf}$$

$$Je \propto \Sigma_{if} |M^2_{if}|\ \Sigma_m |m_{im}|^2 \times \delta(E^N_i + h\nu - E^{N-1}_m - E_{kin})$$

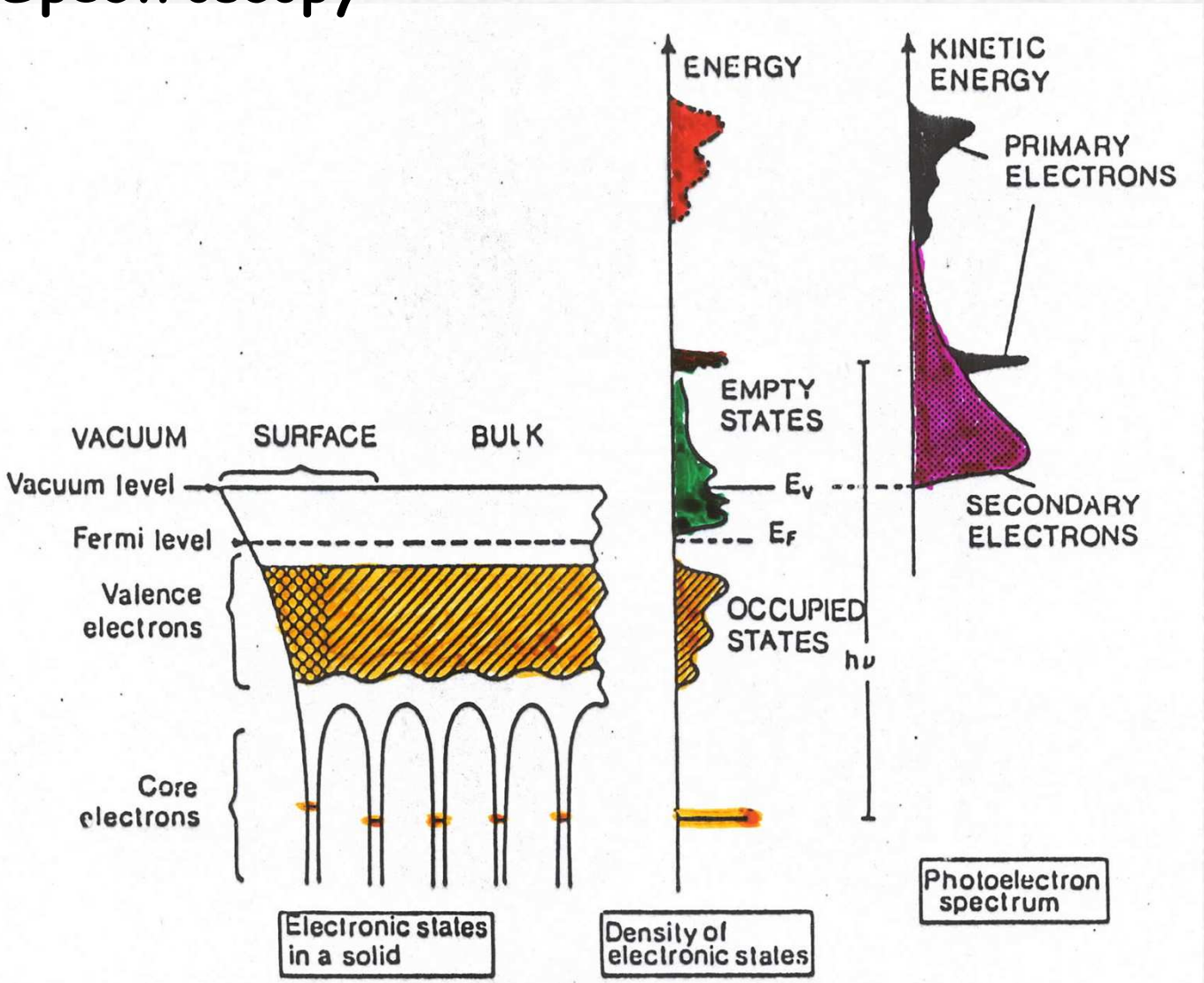
$$A(k, \varepsilon) = \Sigma_m \left(|\langle \Psi^{N-1}_m | c_k | \Psi^N_i \rangle| \right)^2 \times \delta(\varepsilon + E^{N-1}_m - E^N_i)$$

$$Je(k, \omega) \propto \Sigma_{if} |M_{if}|^2\, A(k, E_{kin} - h\nu)\, f(E_{kin} - h\nu)$$

For non interacting particles $A(\varepsilon, k) = \delta(\varepsilon - E_k)$ where $E_k = E^{N-1}_i - E^N_i$

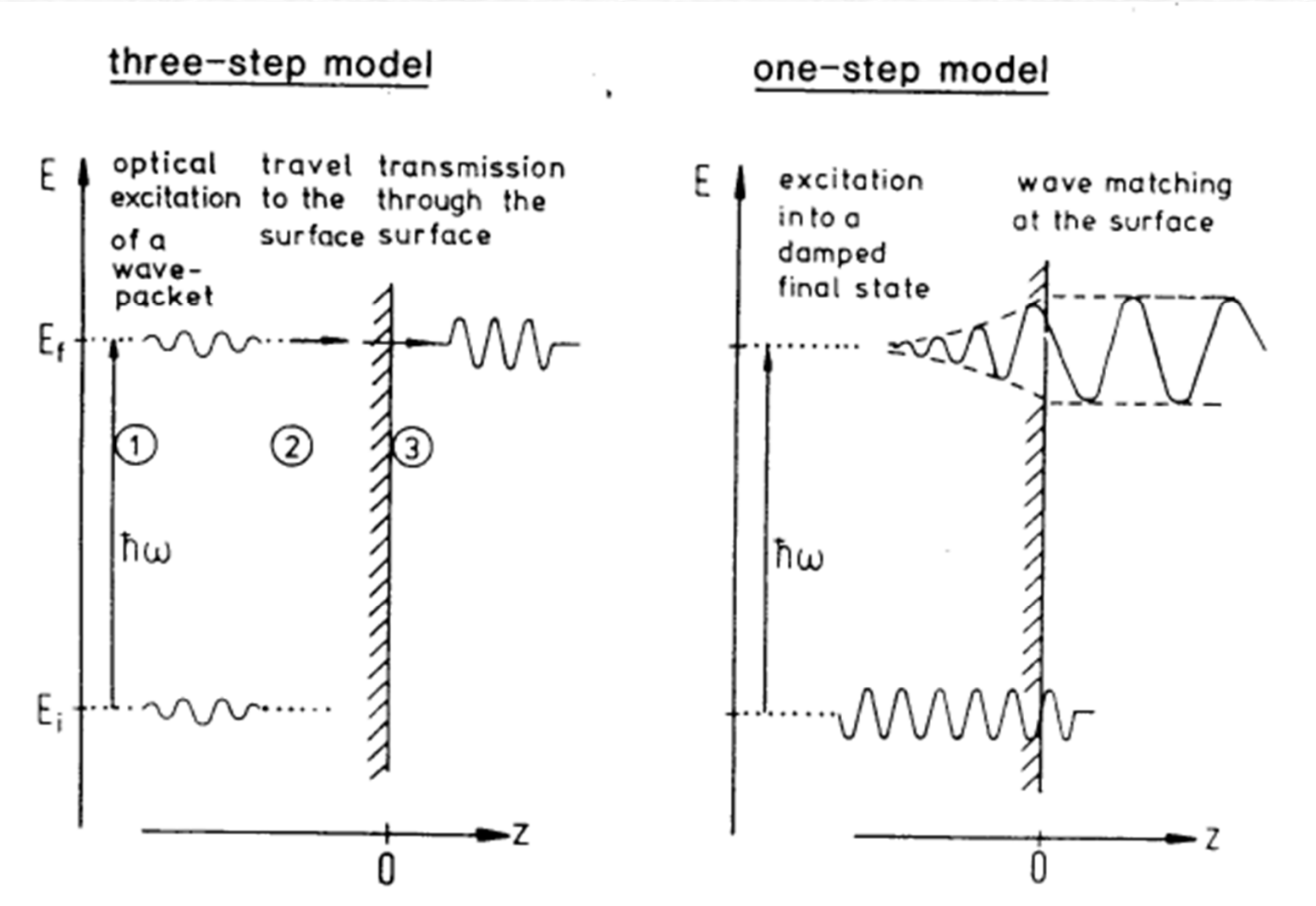
$$A(\varepsilon, k) = 1/\pi\ |\Sigma''(k, \varepsilon)|\ /\ [\,|\varepsilon - E_k - \Sigma'(k, \varepsilon)|^2 + |\Sigma''(k, \varepsilon)|^2]$$

Photoemission Spectroscopy



How real spectra look like: Primary and Secondary Electrons

The Three-Step model 1



The three-step model 2

1. **Dipole transition**

$$Je = \Sigma_{if}\, f(E_i)\,[1-f(E_f)]\, M^2_{if} \times \delta[E_{kin}-(E_f-\Phi)]\, \delta(E_f-E_i-h\nu)\, \delta(k_i+G-k_f)$$

2. **Elastic transport**

$$d(E_f, k) = \alpha\lambda/(1+\alpha\lambda)$$

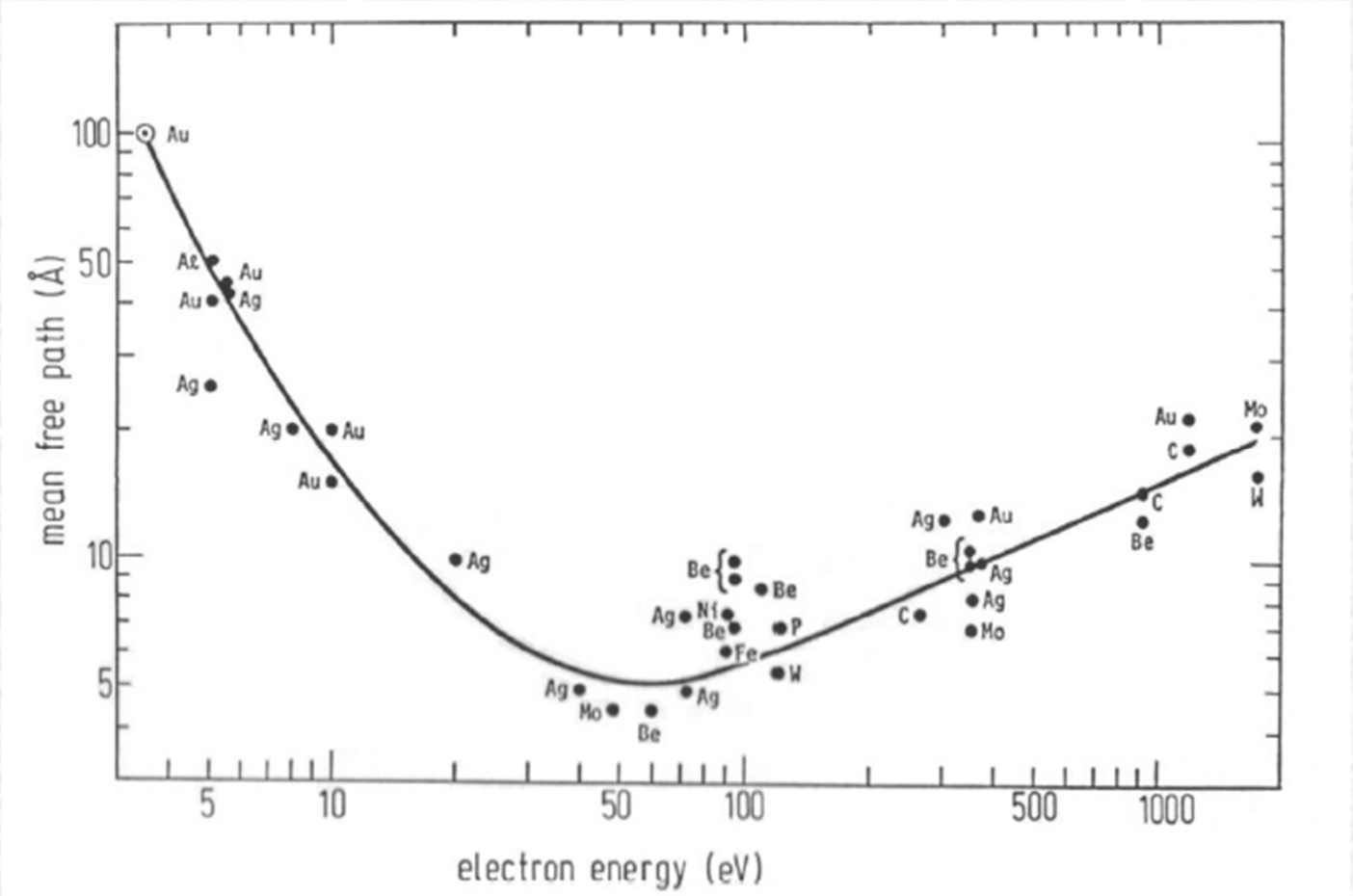
3. **Exit to vacuum**

$$T(E_f, k_{ext}) = \begin{cases} 0 \text{ if } E_f < E_F + \Phi \\ 1/2\ \sqrt{[1-(E_F+\Phi)/Ef]} \text{ if } E_f > E_F + \Phi \end{cases}$$

Total current

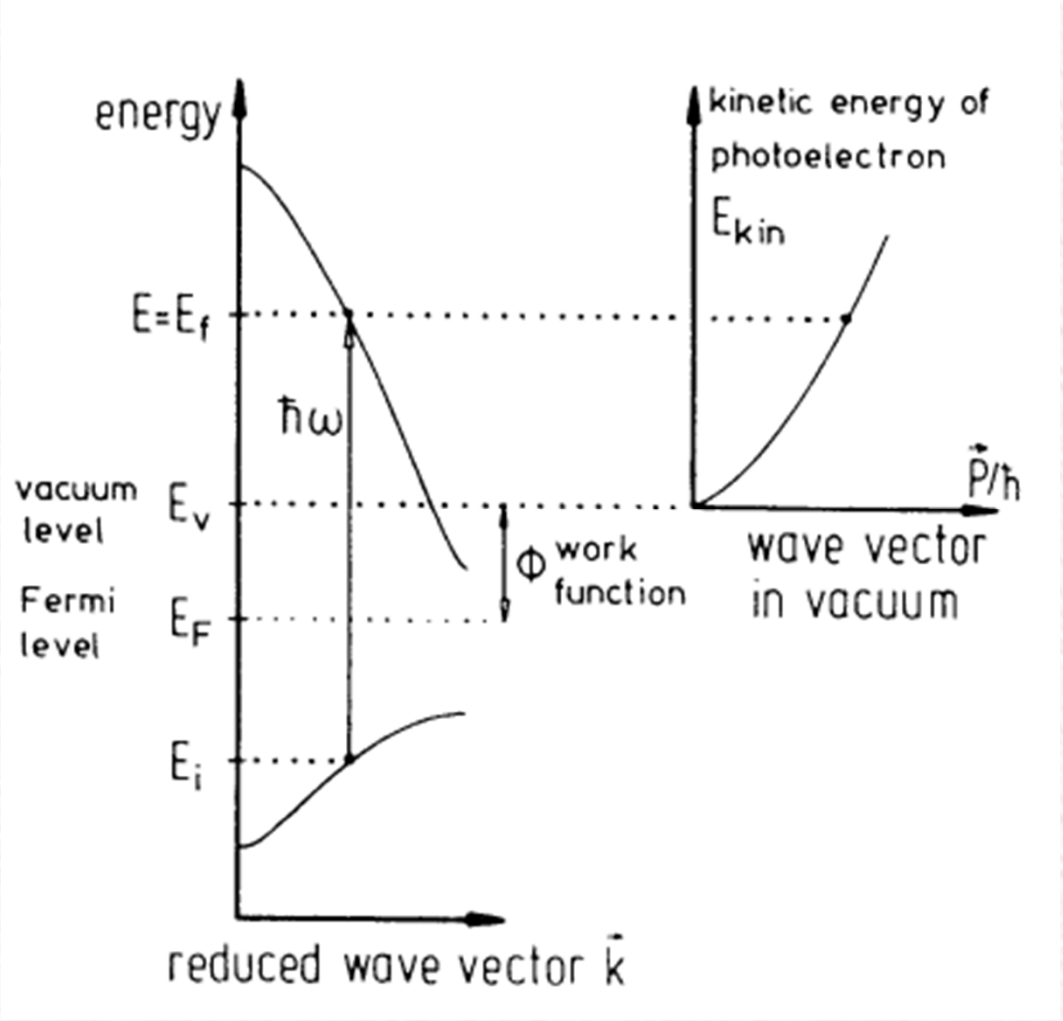
$$Je \propto \Sigma_{if}\, f(E_i)\,[1-f(E_f)]\, M^2_{if} \times T(E_f, k_{ext}) \times d(E_f, k) \times \delta[E_{kin}-(E_f-\Phi)]\, \delta(E_f-E_i-h\nu) \times \delta\,(k_i+G-k_f) \times \delta\,(k^{//}_i+G^{//}-k^{//}_{ext})$$

Photoemission Spectroscopy

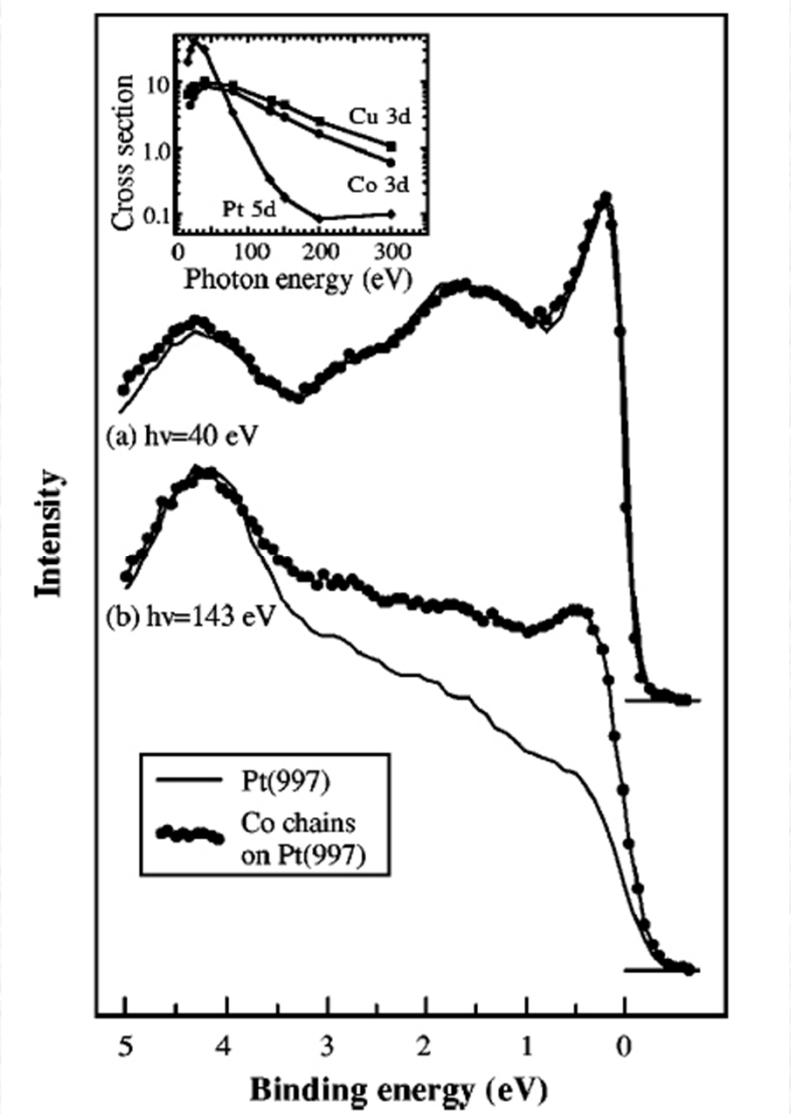


electron mean free path

How to reconstruct the initial state

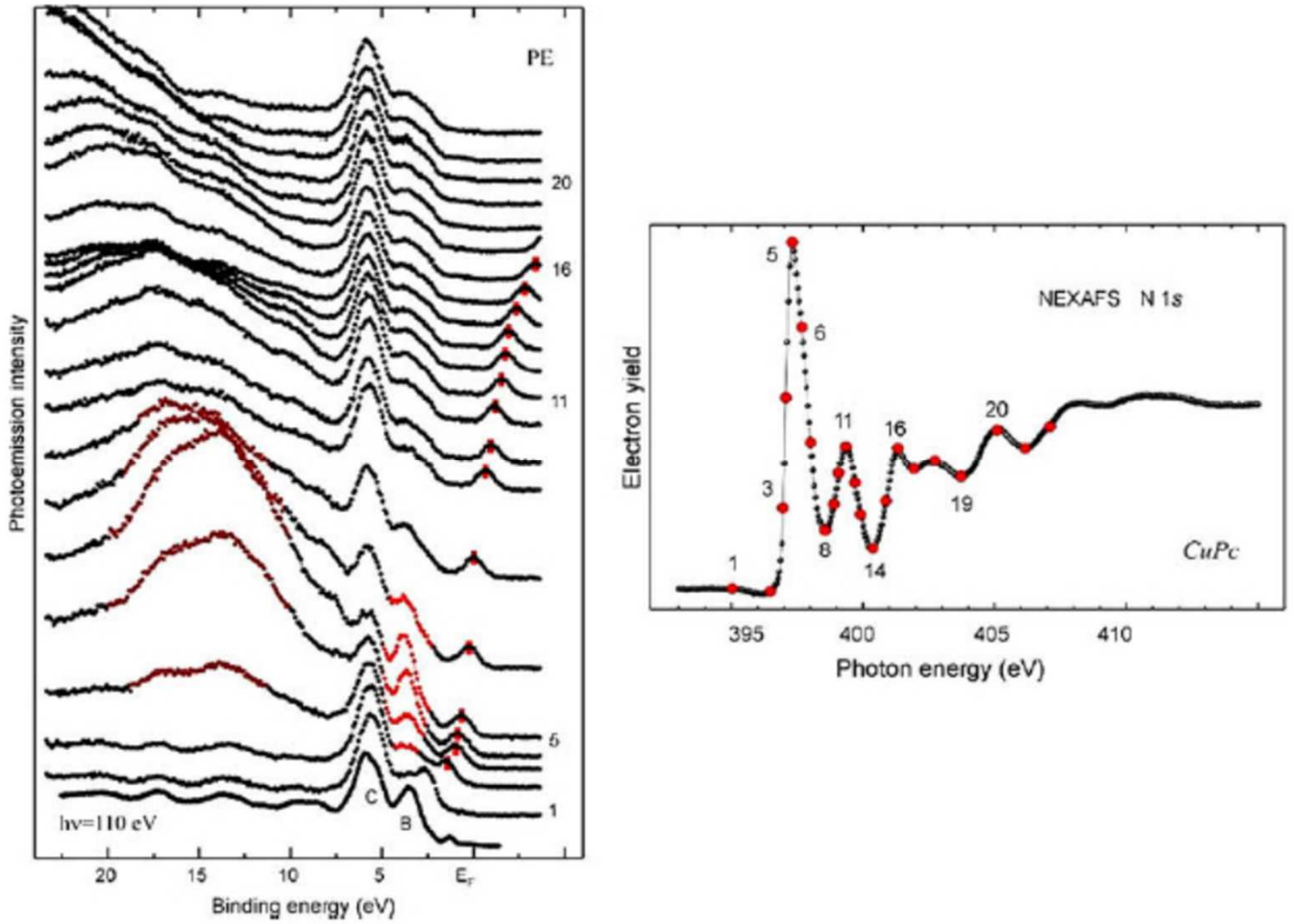


Valence band EDC and Cooper minimum



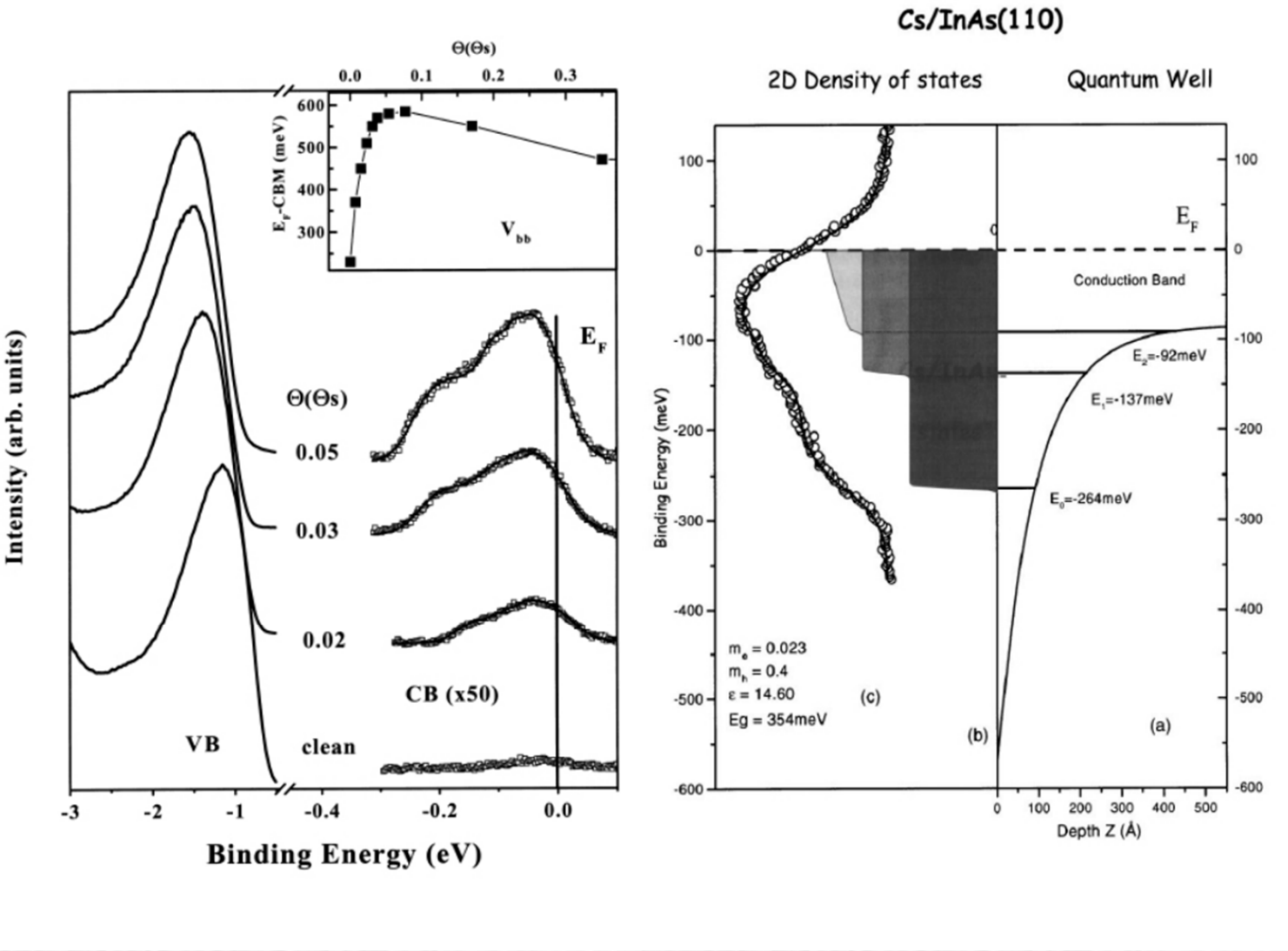
Valence Band EDCs of the clean Pt(997) surface (thin lines) and of Co-nanowires grown on Pt(997) (dots and thick lines), taken at different photon energies

Resonant photoemission

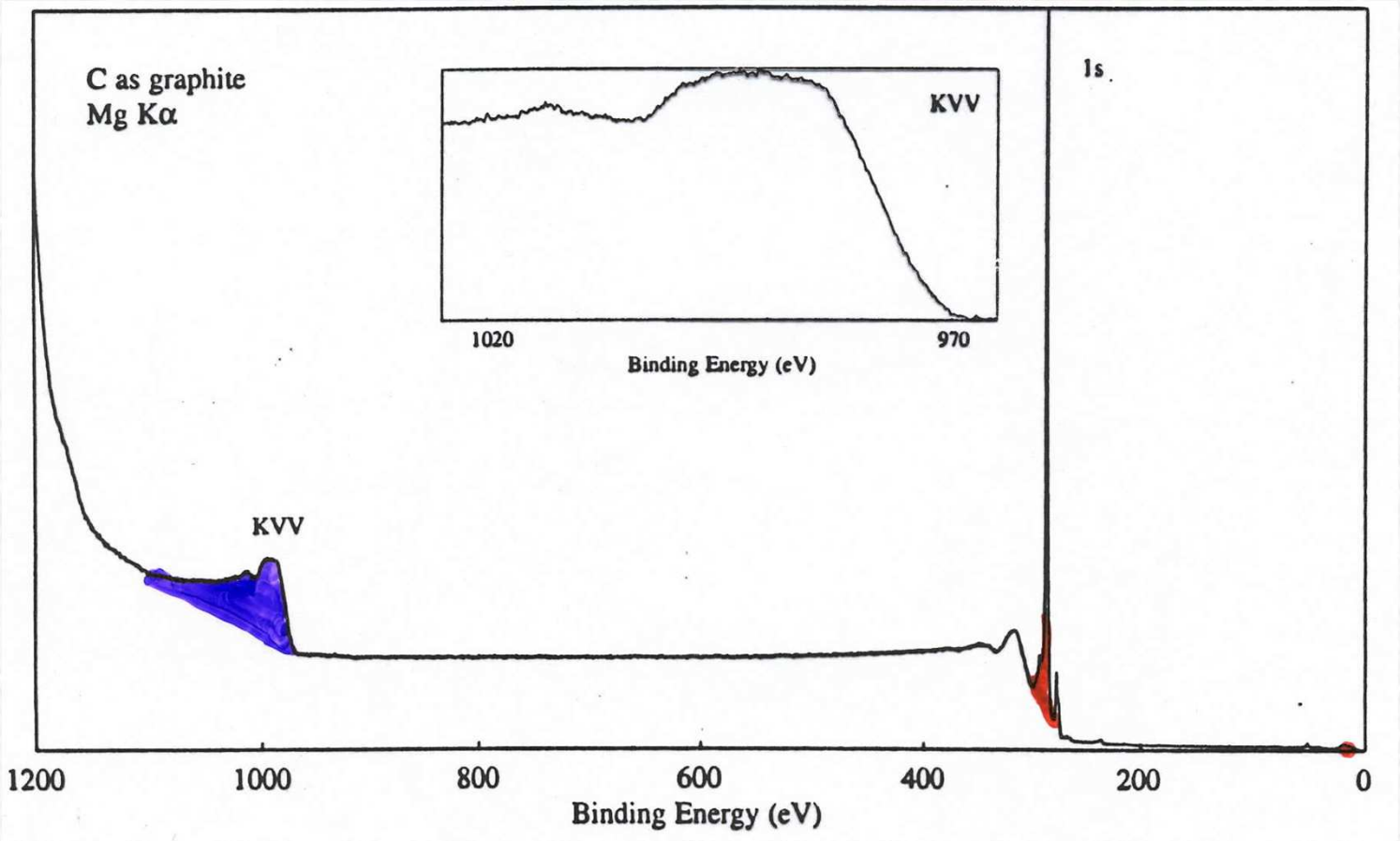


Valence Band EDCs of a CuPc thin-film taken at different photon energies (left panel) and X-ray Absorption Spectroscopy (XAS) from the same CuPc across the N K-edge (right panel).

2D electron gas spatially confined Cs/InAs(110)

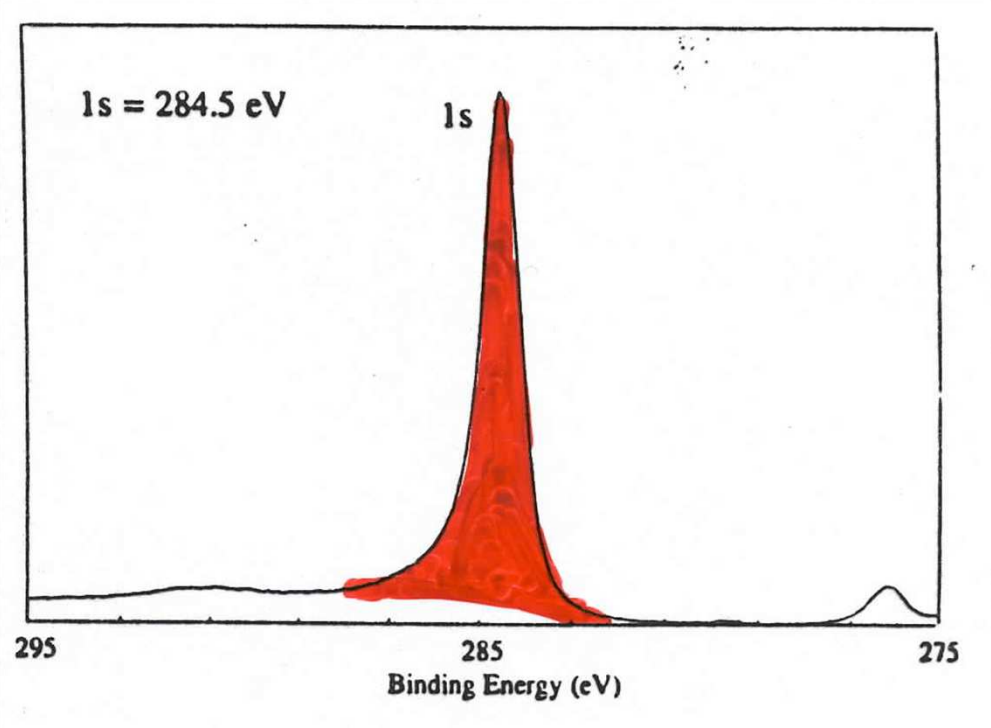


Wide XPS spectrum of graphite (C)



Photoemission Spectroscopy

Core level XPS spectrum of graphite (C)

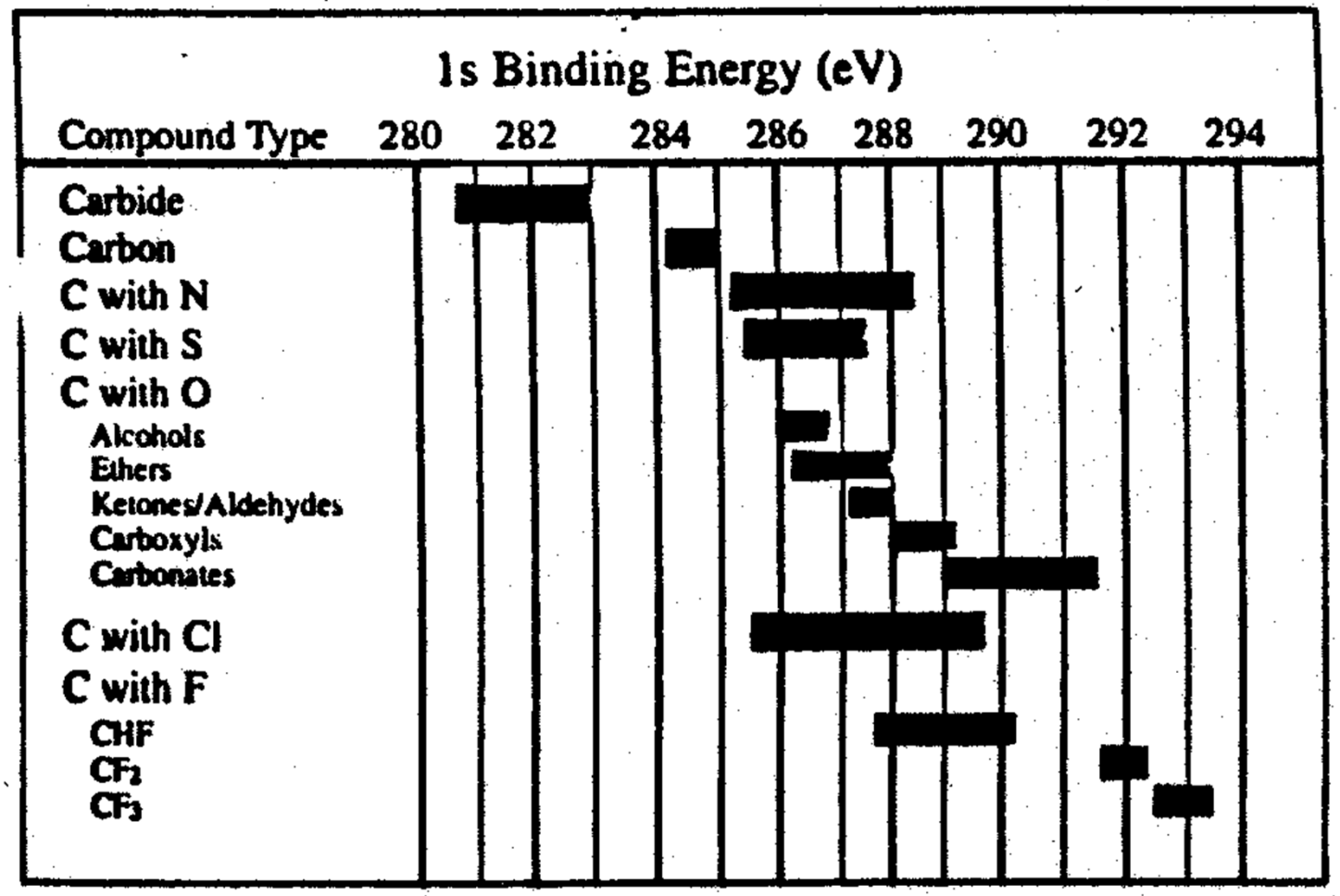


The singlet *C 1s* line is characterized by:

1) A specific binding energy which reflects the specific atomic species (C) in a specific chemical environment

2) A finite width reflecting the instrumental resolution, lifetime broadening and other many-body effects

Photoemission Spectroscopy: Chemical Shift (ΔE_b)



How the C 1*s* binding energy reflects differing chemical environme nt local to the excited C sites

Core Levels, chemical shift

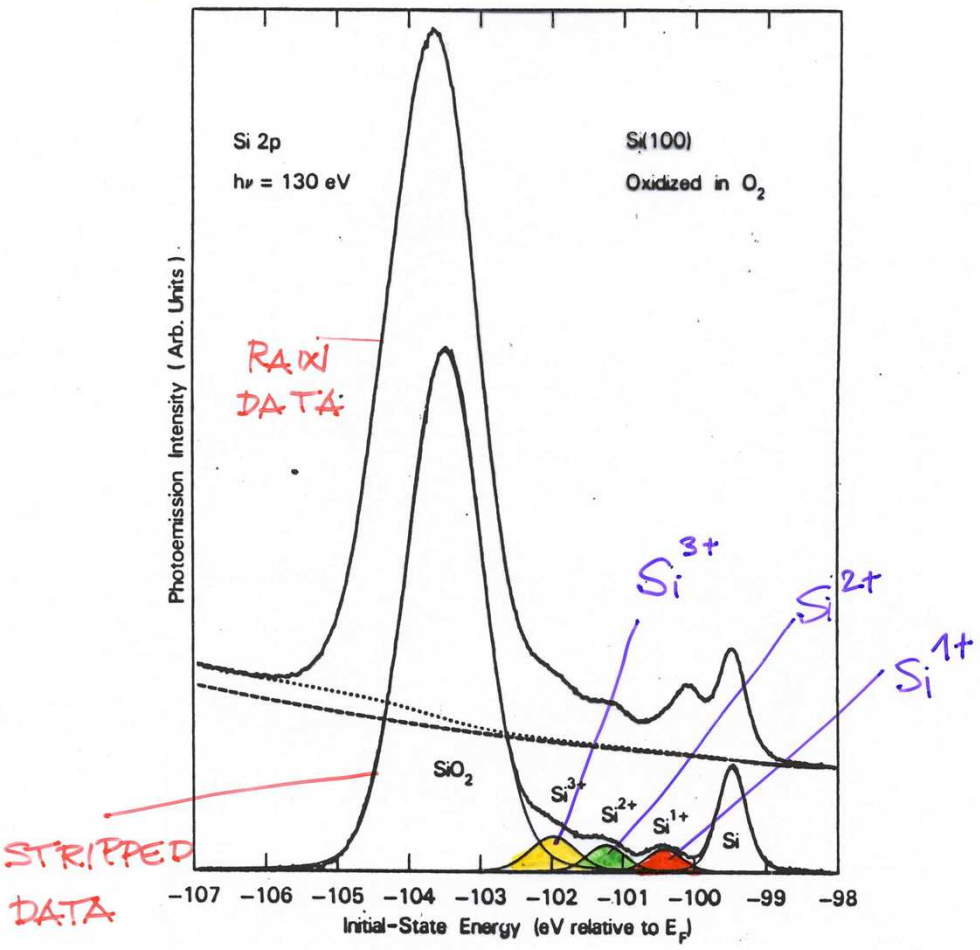
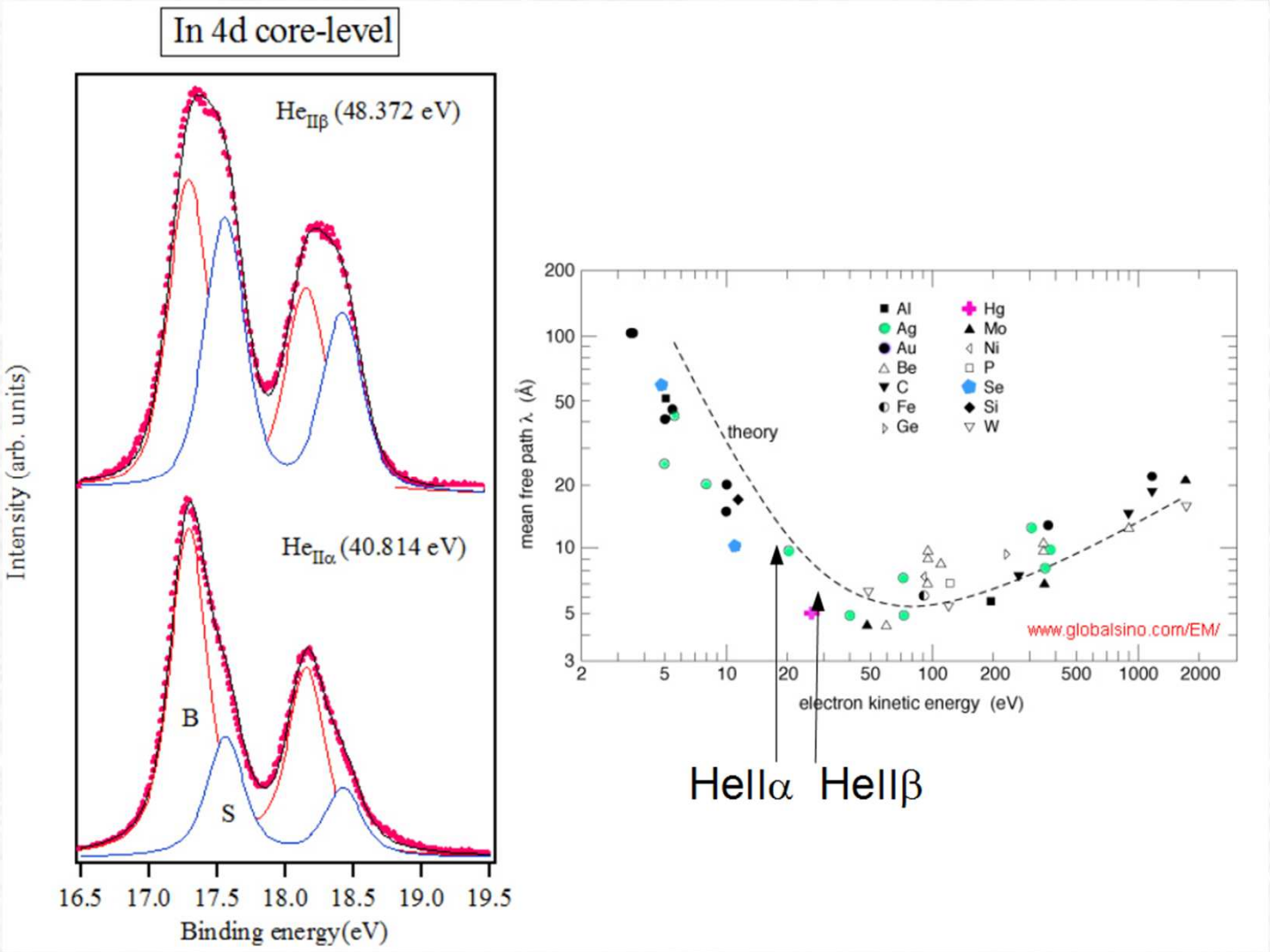


FIG. 1. Intermediate-oxidation states at the SiO_2/Si(100) interface, identified by their Si 2*p* core-level shifts. The top curve represents the raw photoemission data for the Si $2p_{1/2,3/2}$ core levels. The bottom curve has the Si $2p_{1/2}$ line and the secondary electron background subtracted. All three intermediate-oxidation states are seen. For a truncated bulk structure only Si^{2+} would be present since the Si(100) surface has two broken bonds per atom.

The Si 2*p* line is characterized by the occurrence of 5 chemically distinct components which reflect different chemical states of the Si atoms at the interface

Surface core level shift vs. mean free path In 4d



High-resolution In-4d core-levels at freshly cleaved InAs(110), taken with He_{IIa} and He_{IIb} radiation; Voigt-profiled fit with surface (S, blu lines) and bulk (B, red lines) doublet components (left panel)

Photoemission Spectroscopy: Core Levels

Spin-Orbit Splitting

(iii) *Degeneracies determine relative intensities of peaks comprising doublet*

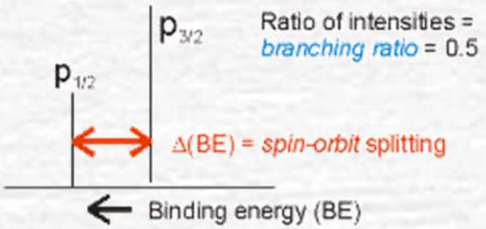


Fig. 6.5

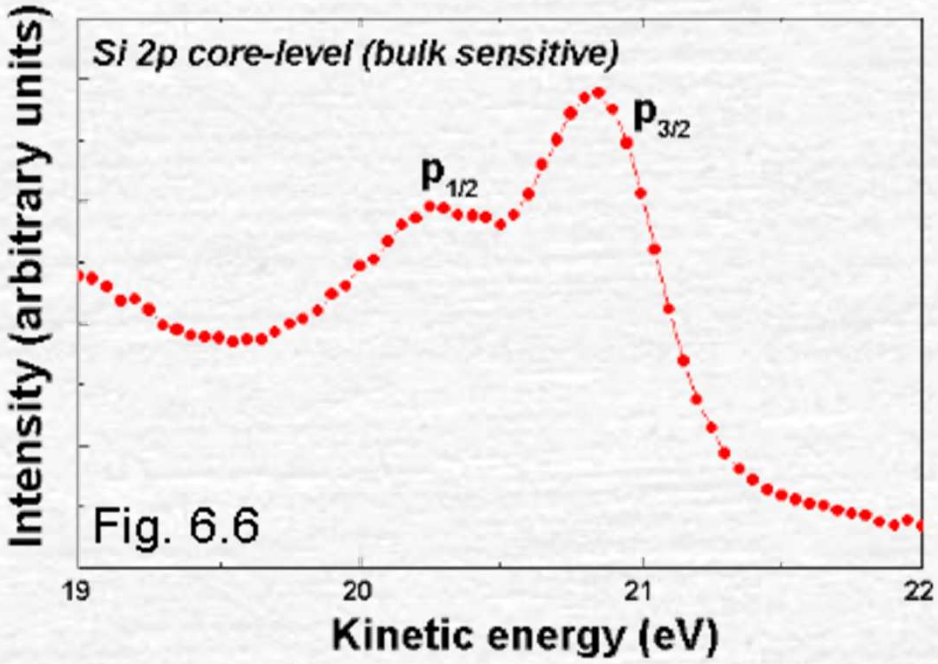
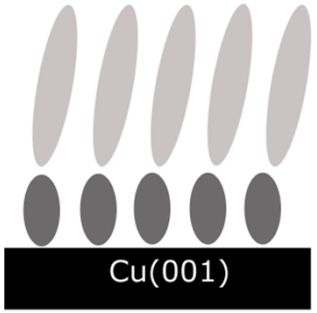
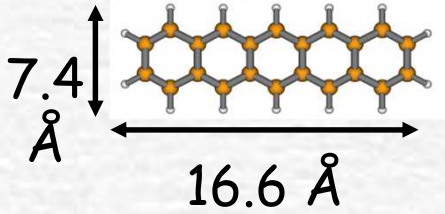


Fig. 6.6

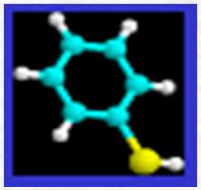
valence PE vibrational spectrum

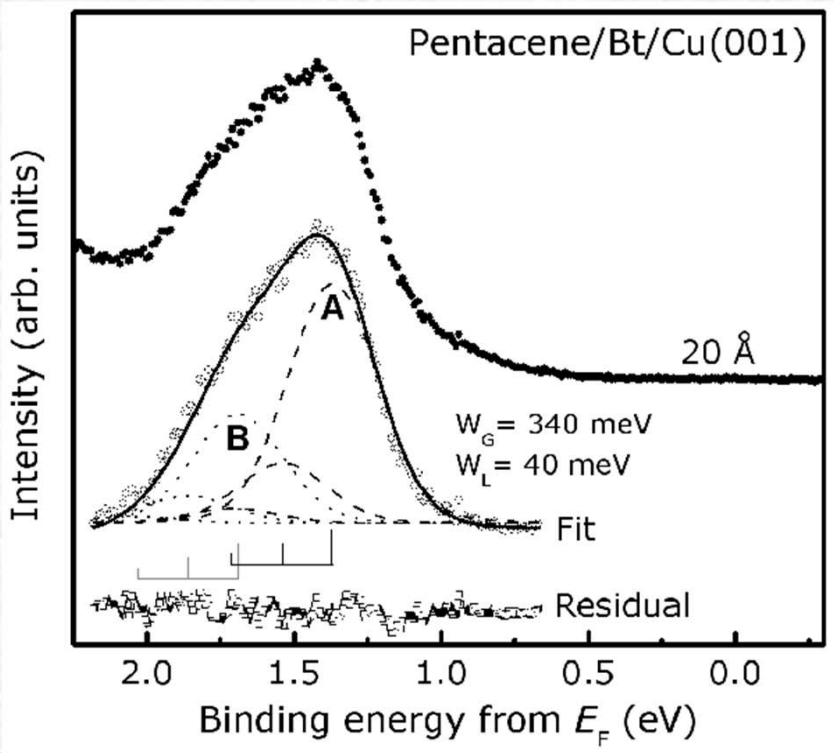


pentacene: $C_{22}H_{14}$



benzene-thiol: C_6H_5-SH

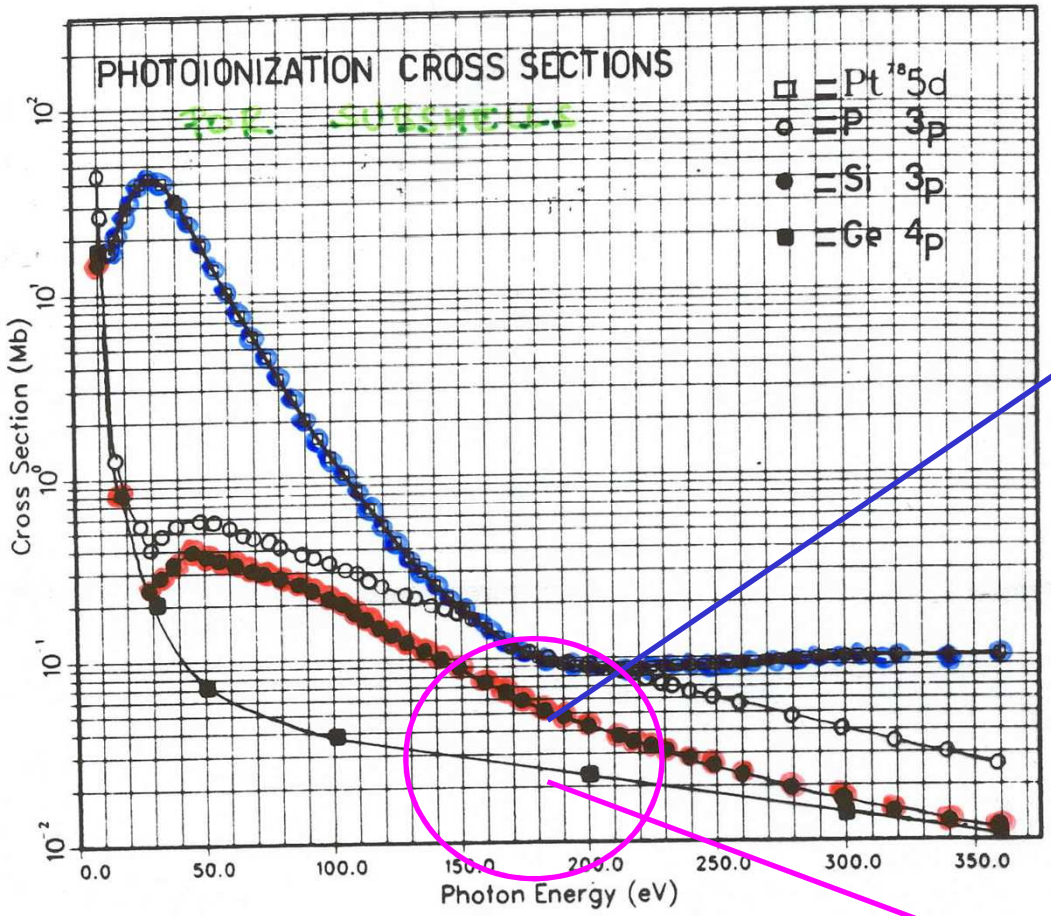




Betti, Kanjilal and Mariani, J. Phys. Chem. A **111**, 12454 (2007)

Cooper Minimum Photoemission

It is possible when one of the valence band orbital shows a Cooper minimum in the photoionization cross section



. Photoionization cross section for 4d and 5d subshells in the energy range 0–200 eV compared to the cross sections for the 3ps and 4sp valence states of the semiconductors [21].

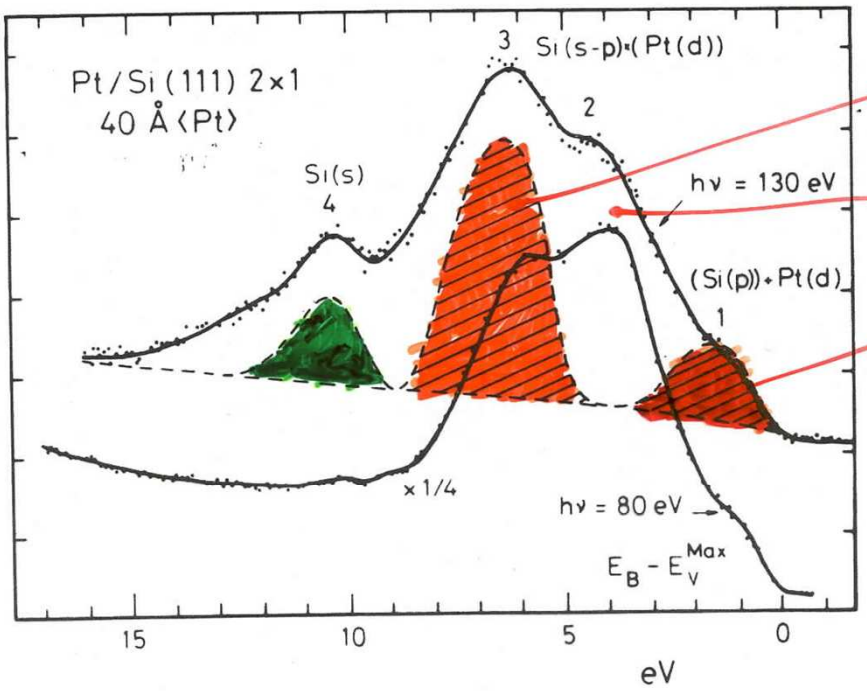
Cooper minimum in the Pt 5*d* cross section

A **Cooper minimum** exists when the **radial part** of the **orbital wave function** exhibits a **node**

The Pt 5*d* and Si 3*p* cross sections are comparable

Cooper Minimum Photoemission

A joint analysis of VB photoemission spectra taken at and off the Cooper minimum enables one to disentangle the differing site- and orbital-specific contributions



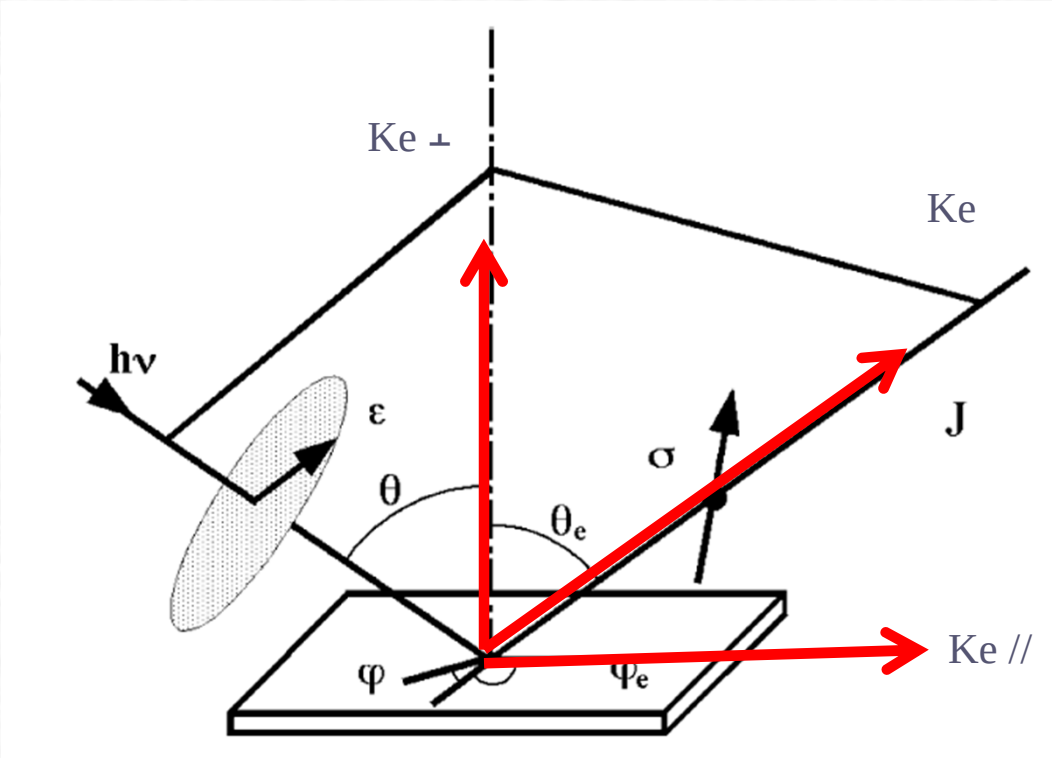
Pt 5*d* anti-bonding

Pt 5*d* non-bonding

Pt 5*d* bonding

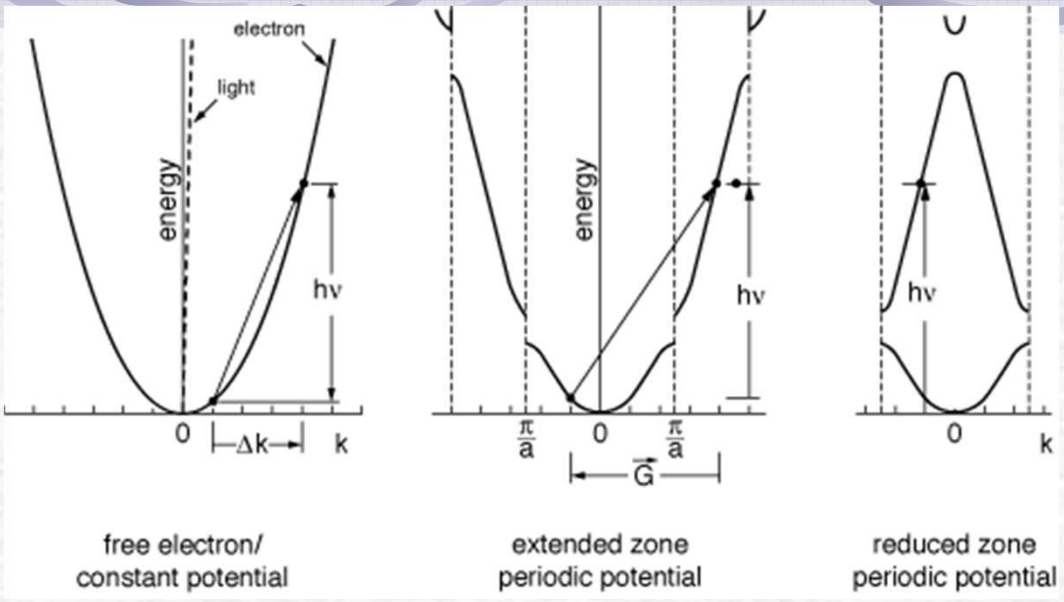
. Analysis of the Si sp partial DOS at the Pt–Si(111) reacted interface (40 Å Pt–Si(111) at room temperature). The top panel displays the CM and the $h\nu = 80$ eV photoemission data, and a three-peak partial DOS that accounts for the Si hybridized 3sp charge at the interface; a gap is present in correspondence to the localized Pt 5d states. The same three-peak partial DOS is then self-convoluted and compared to the integrated Si $L_{2,3}VV$ lineshape. The correspondence of all peaks and relative intensities (a part of the known reduction of the Si 3s contribution) confirms the CM derivation of the Si sp partial DOS [159].

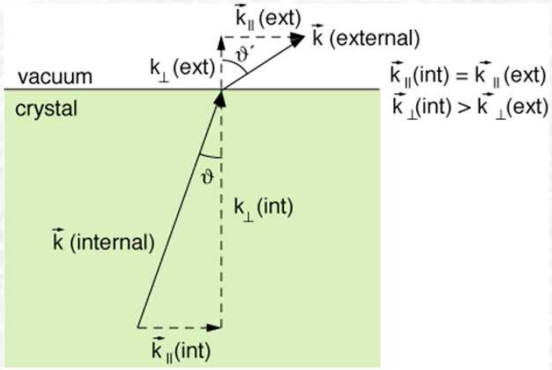
Angular resolved photoemission



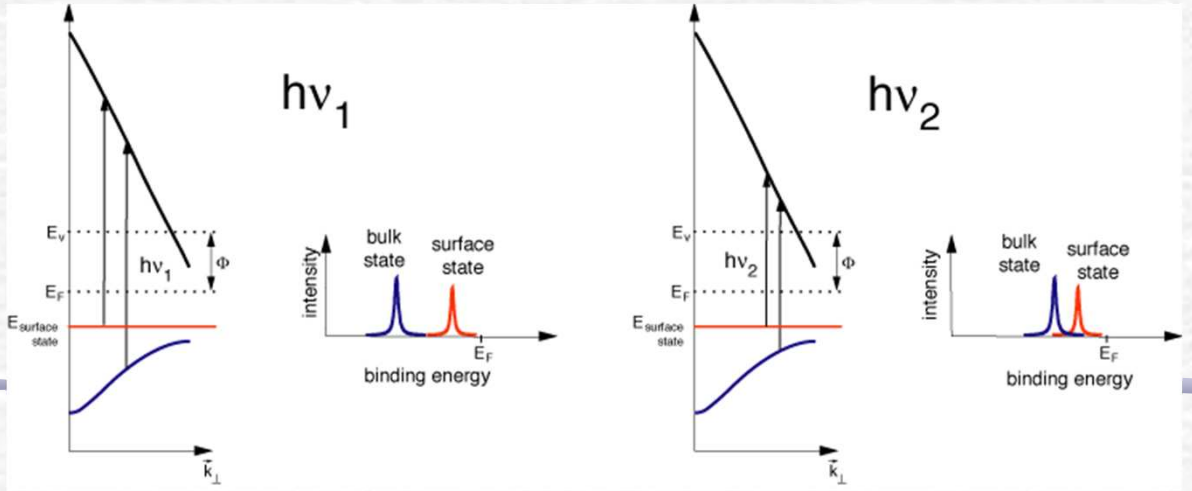
angular resolved photoemission

How to photo-excite electrons from a crystal in a periodic potential, by photoemission



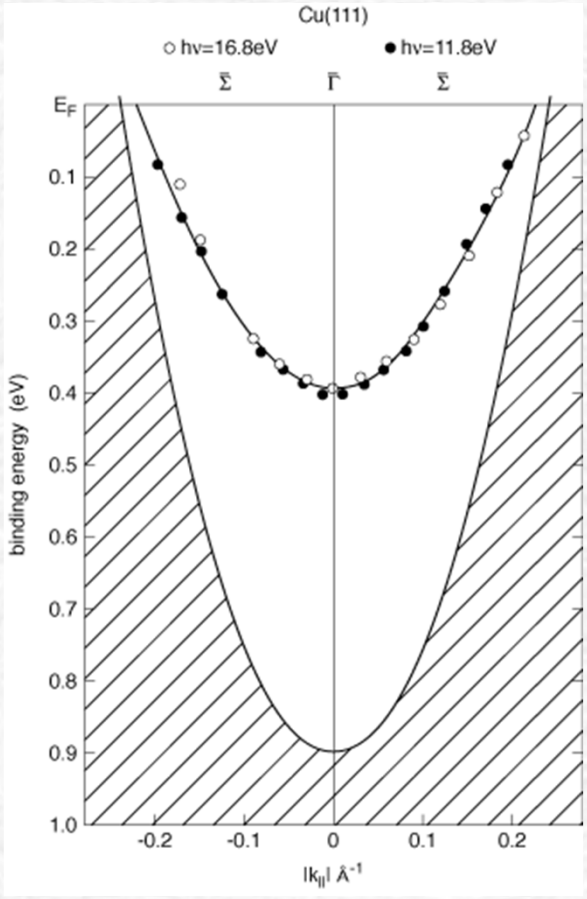


$$\vec{k}_{||i} = \vec{k}_{||f} = \sin(\Theta)\sqrt{\frac{2m}{\hbar^2}}\sqrt{E_{kin}} = \sin(\Theta)\sqrt{\frac{2m}{\hbar^2}}\sqrt{h\nu - E_{bin} - e\Phi}$$

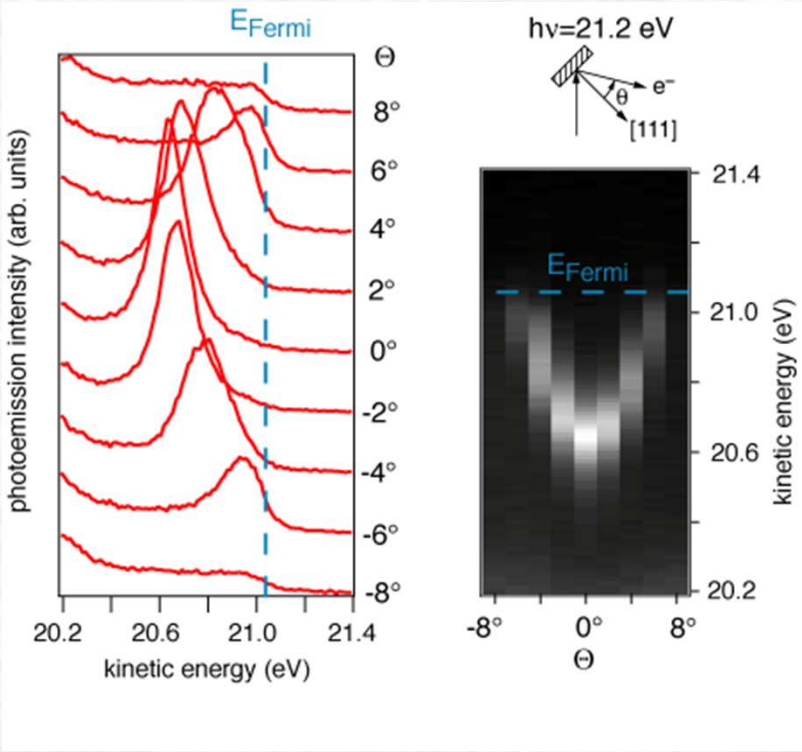


graphs from Ph. Hoffmann

electronic surface states at Cu(111)

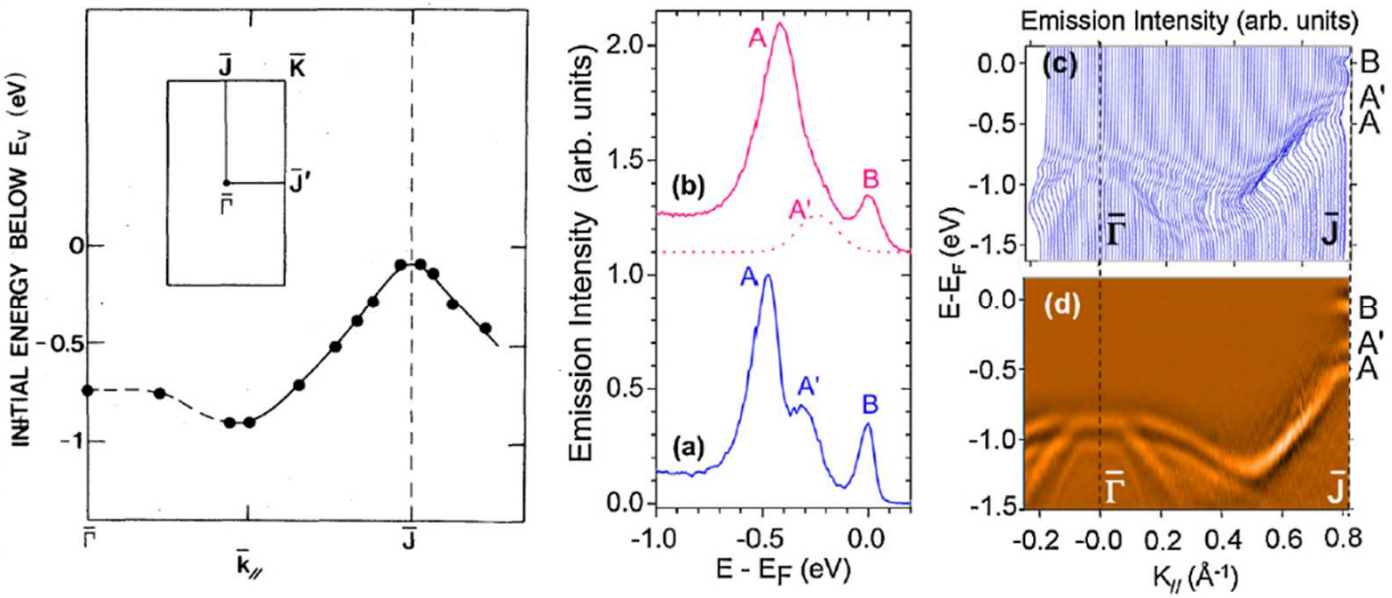


S.D. Kevan, Phys. Rev. Lett. 50,526 (1983).



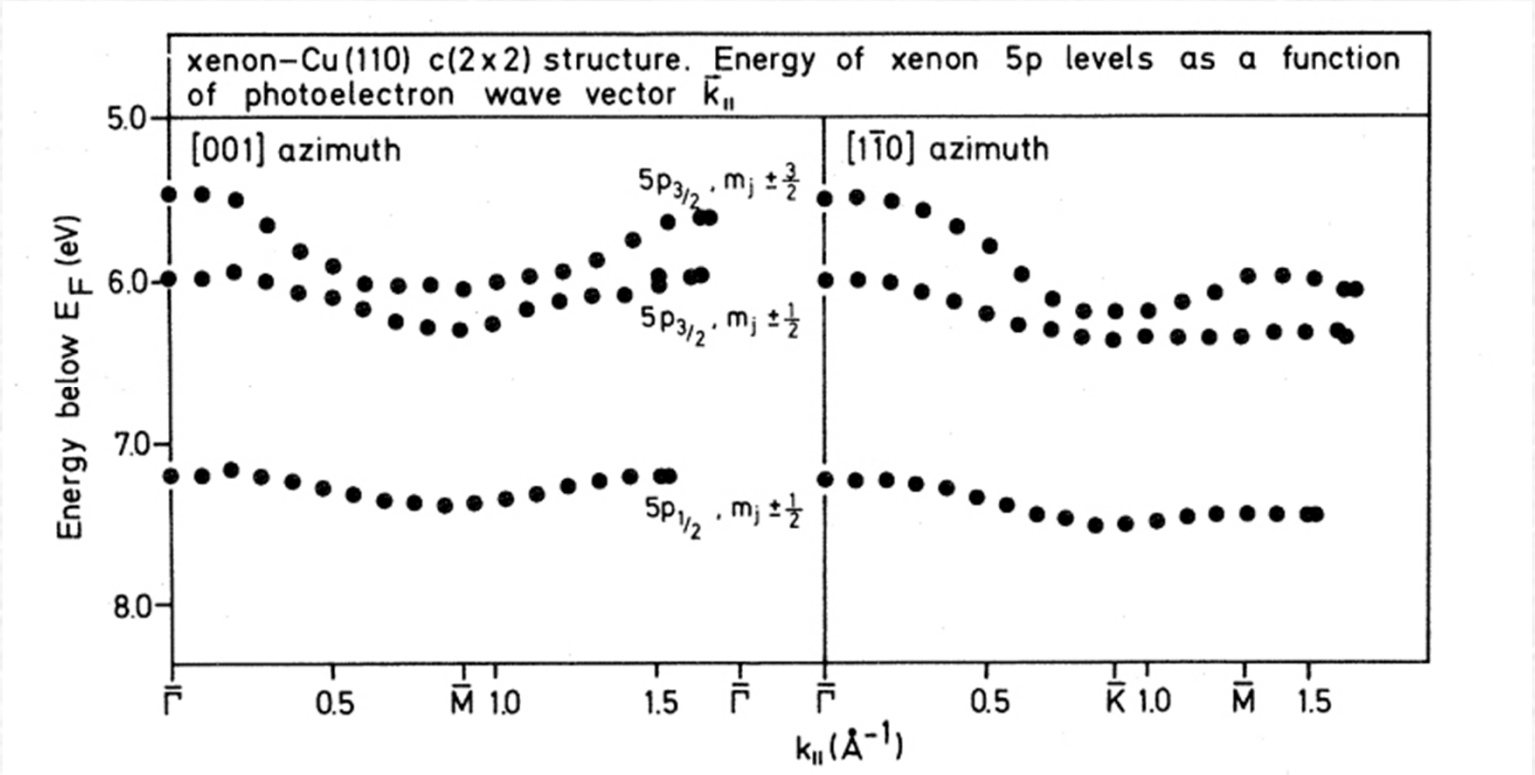
quasi-free electron surface state on Cu(111),
Schockley state, *s-like*

Dangling bonds Si(111)-(2x1)



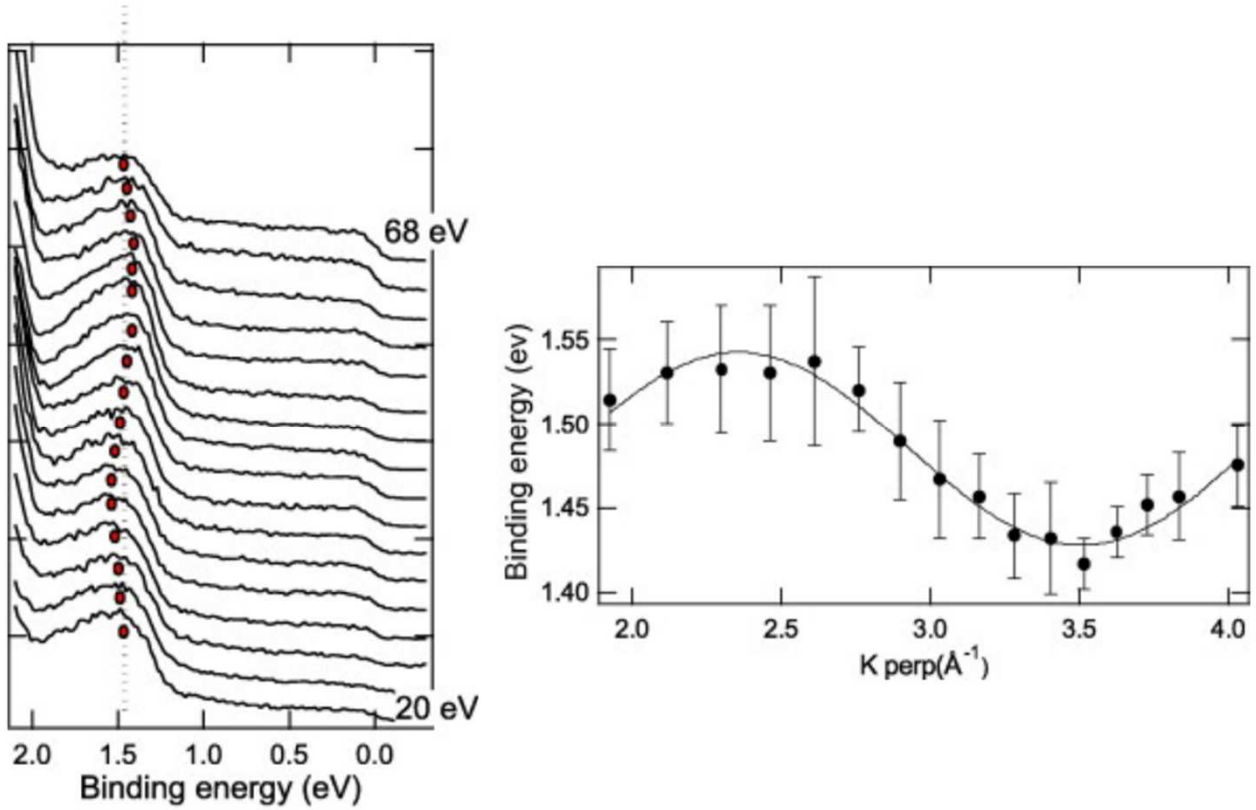
Dangling-bond surface state dispersion at the Si(111)-(2x1) reconstructed surface along the ΓJ direction of the Surface Brillouin Zone (SBZ). One of the first experimental ARPES dangling-bond dispersion (left panel); recent high-resolution ARPES dangling-bond dispersion.

Physisorbed Xe c(2x2)/Cu(110)



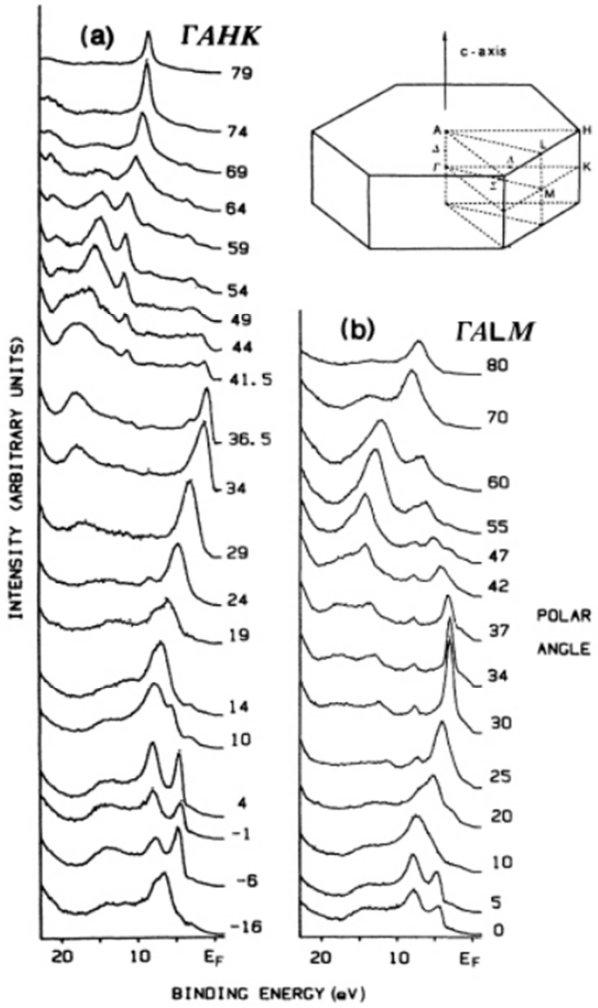
Experimental band structure of the 5p levels of Xe physisorbed in an ordered c(2×2) structure onto the Cu(110) surface. ARPES bands

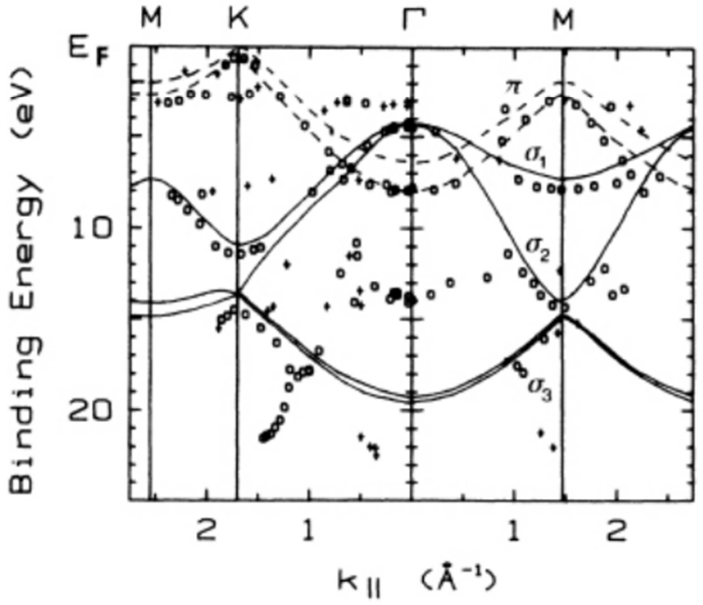
Pentacene HOMO on Cu(119)



2-nm thick pentacene film grown on Cu(119). ARPES selection of spectra taken at normal emission and varying the photon energy (left); highest-occupied molecular-orbital (HOMO) band dispersion along $k_{\perp}$ (right).

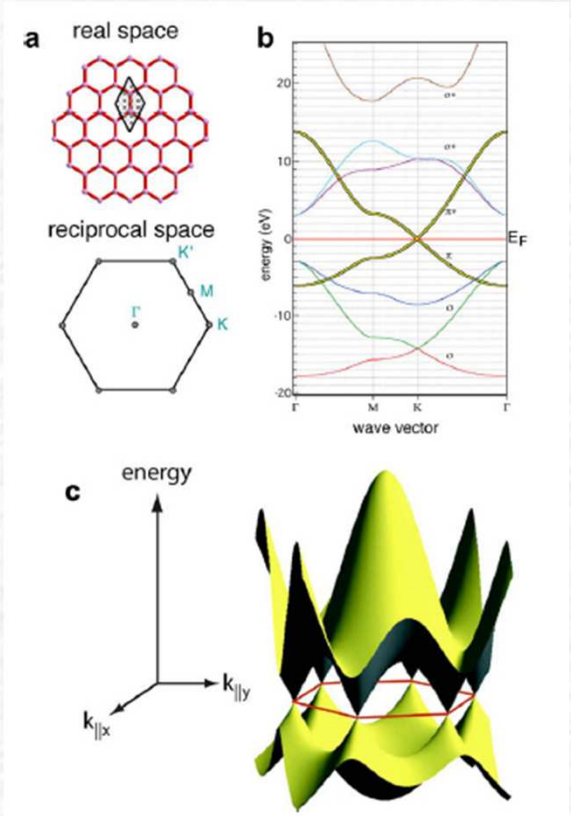
ARPES graphite (HOPG)

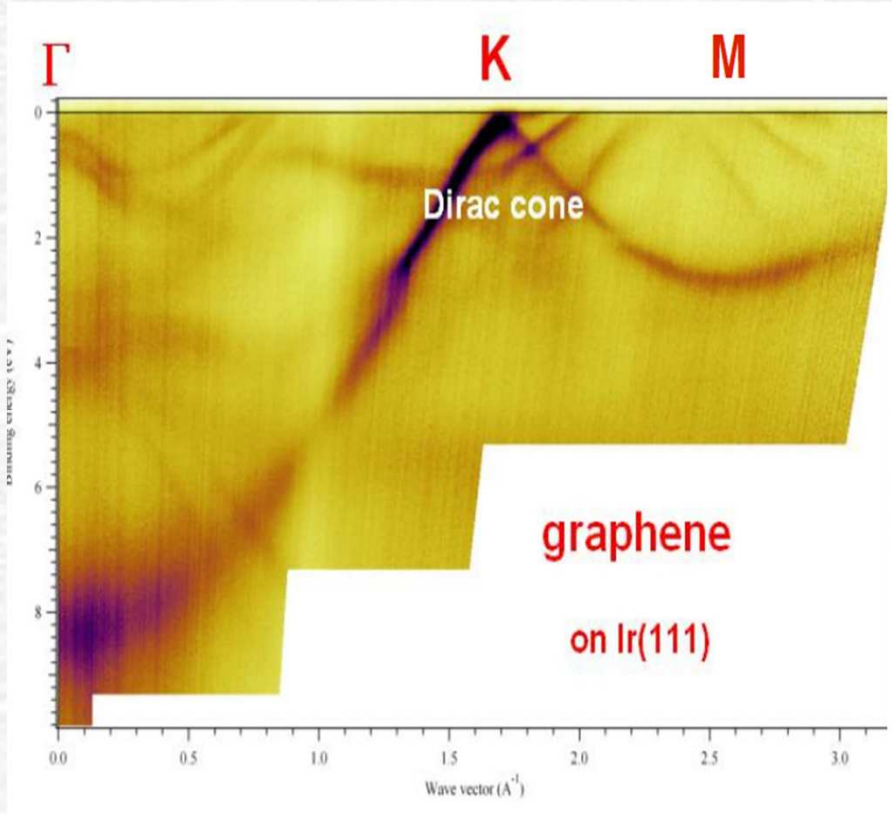


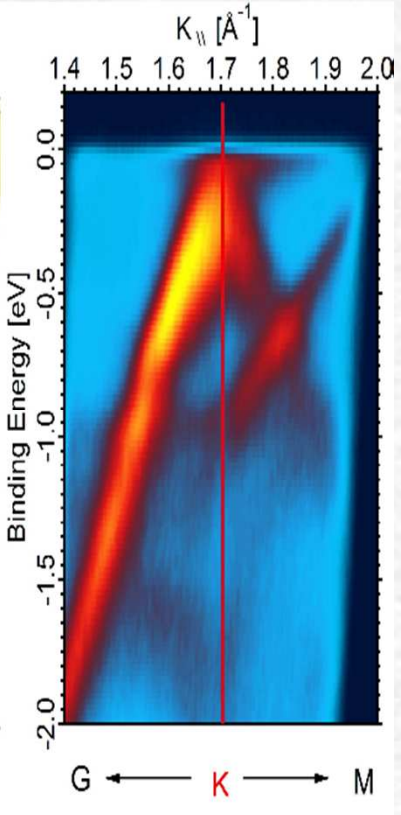


Valence band of graphite (HOPG), stacking of the ARPES spectra as a function of polar angle (left) and experimental band structure (right).

Graphene band structure

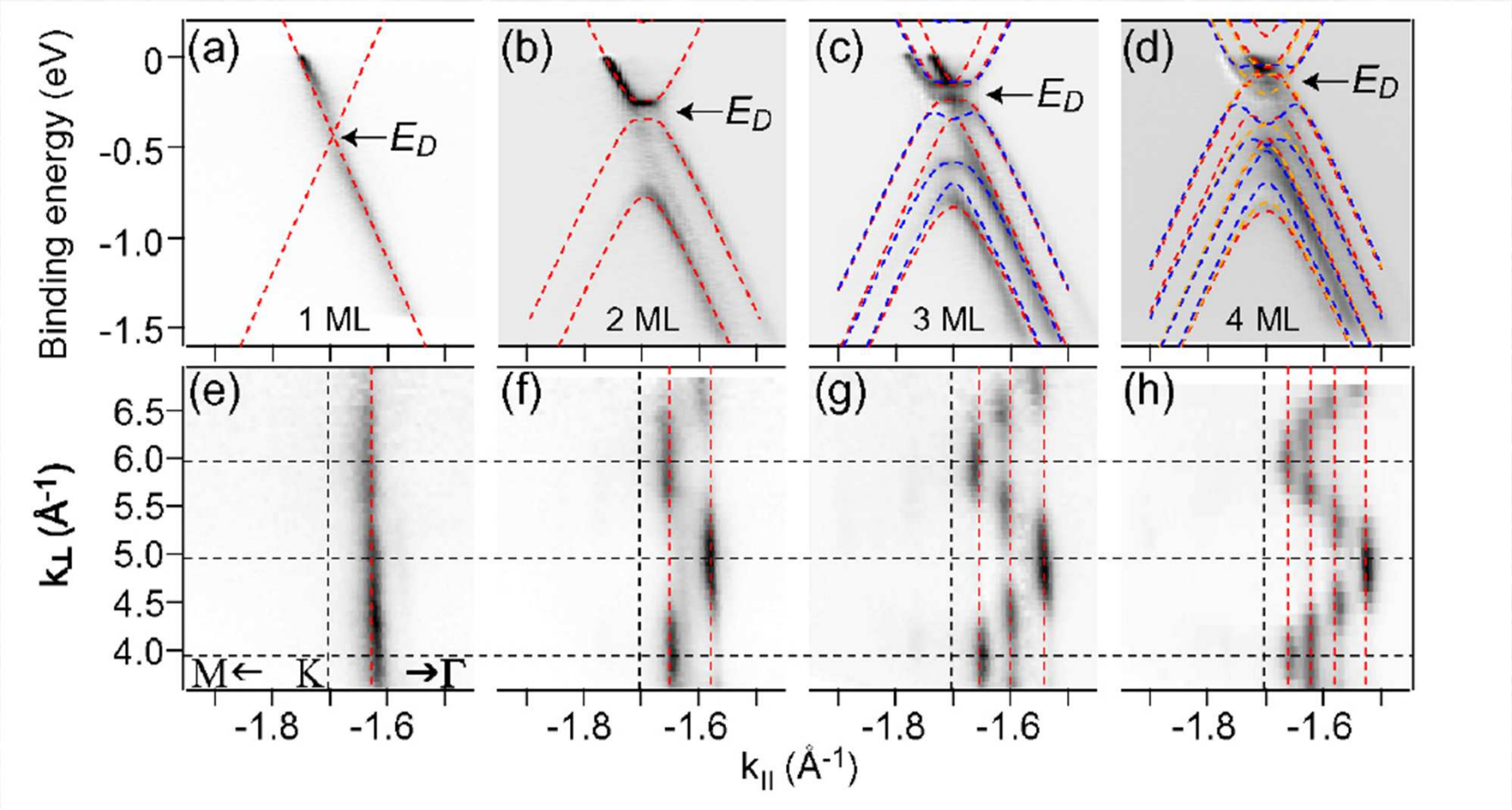






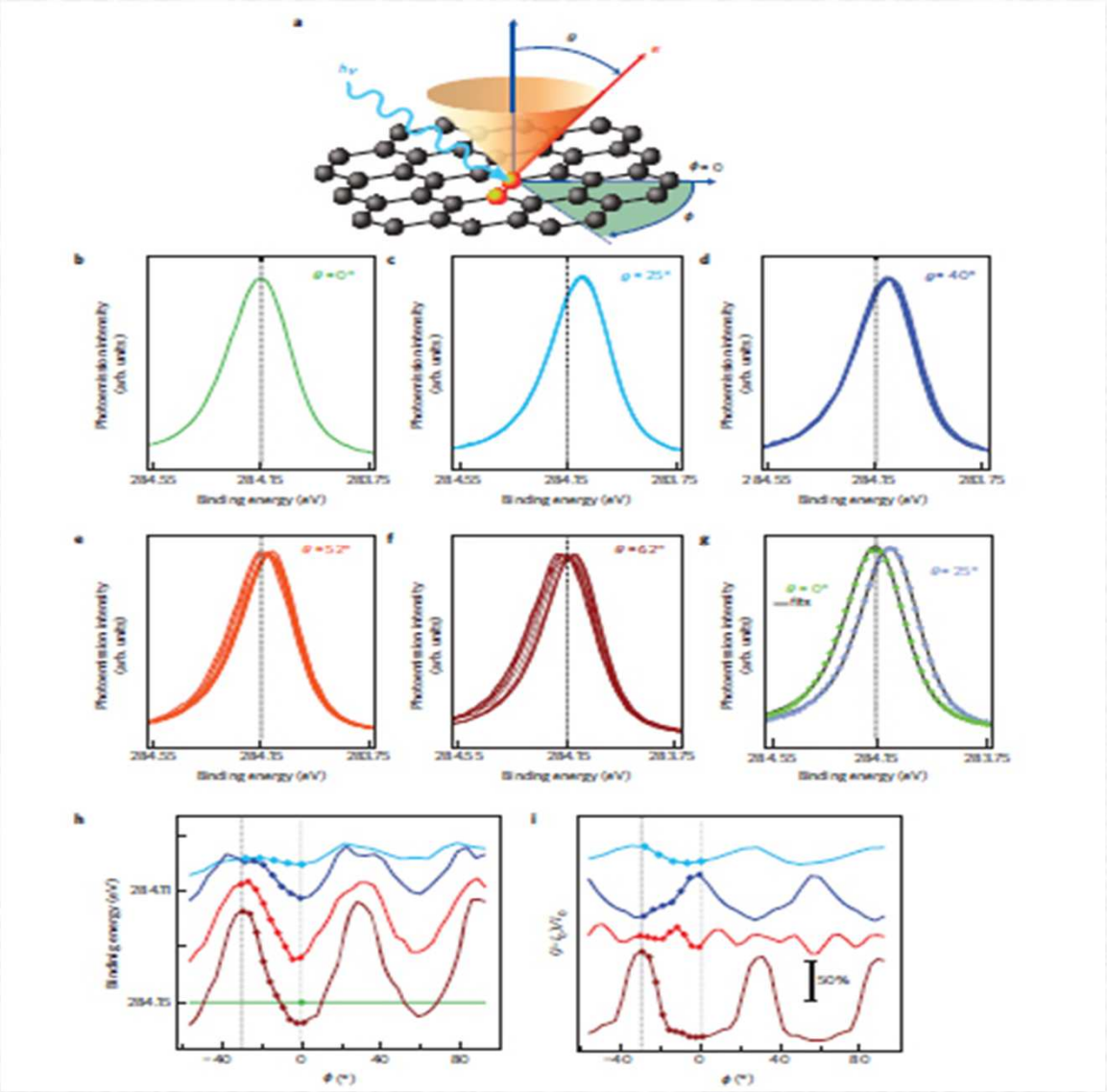
Graphene band structure along GKM and zoom of the Dirac cone around the K point of the SBZ. ARPES data taken with high-resolution ARPES and a He discharge source

Band formation in graphene multilayers



. Formation of an electronic band, stepwise: from 1-layer (extreme left) to 4-layer (extreme right) graphene band structure along across the Dirac point.

K shell dispersion in graphene



Spectral function of the C 1s core-level in graphene as a function of the emission polar angle

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The End

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