(192)

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Cours/Lecture Series

1987-1988 ACADEMIC TRAINING PROGRAMME

LECTURER : W. STEINMANN / University of Munich
TITLE : Applications of synchrotron radiation
DATES : 27, 28 & 29 October
TIME : 11.00 to 12.00 hrs
PLACE : *LEP Auditorium bldg 30, 7th floor*

ABSTRACT

1. ***Introduction***
   Properties of SR, development of SR sources, monochromators
2. ***Spectroscopy with SR***
   Atoms, molecules, solids, surfaces : absorption, photoemission
3. ***Non-spectroscopic applications of SR***
   Microscopy, lithography, topography, angiography.

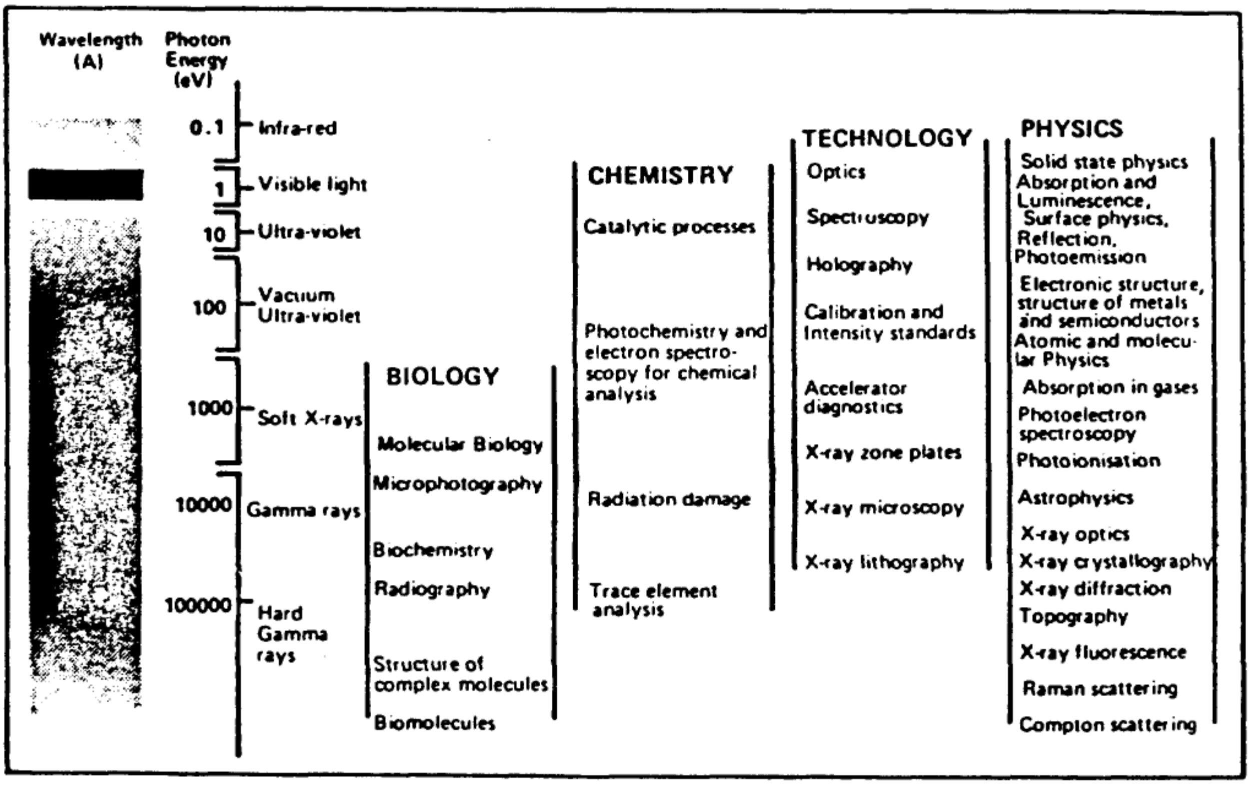


Fig. 1 Experimental uses of the synchrotron radiation spectrum. The unique properties of sychrotron radiation including its broad spectrum extending from the infrared to the x-ray region make it a unique research tool for a broad range of disciplines. It can be useful in any scienfitic investigation where the structure or nature of a material or specimen can be examined by means of its interaction with electromagnetic radiation. The spectrum graphically illustrates the range of wavelengths available from a typical synchrotron radiation source. Some of the disciplines and research subjects that make use of the synchrotron radiation are also shown, the titles placed to correspond, very approximately, with the part of the spectrum that is utilized.

Early History of Synchr. Rad.

1944 Ivanenko and Pomeranchuk:
Radiation loss limits $E \leq 500$ MeV
for betatron (calculation)

1945 Blewett:
Radiation loss observed (not radiation)
100 MeV Betatron (G.E.)

1946 Schwinger: $P \sim \frac{E^4}{R^2}$
Spectrum extends
to X-ray region for $E = 1$ GeV

1947 (24. April) Pollock et al.
Synchr. radiation observed
70 MeV Synchrotron (G.E.)

1949 Schwinger:
Theory of synchr. rad.

$\psi \approx \gamma^{-1}$ $\lambda_c = \frac{4\pi R}{3\gamma^3}$

$\gamma = \frac{E}{mc^2}$ $(\lambda > \frac{\lambda_c}{4})$

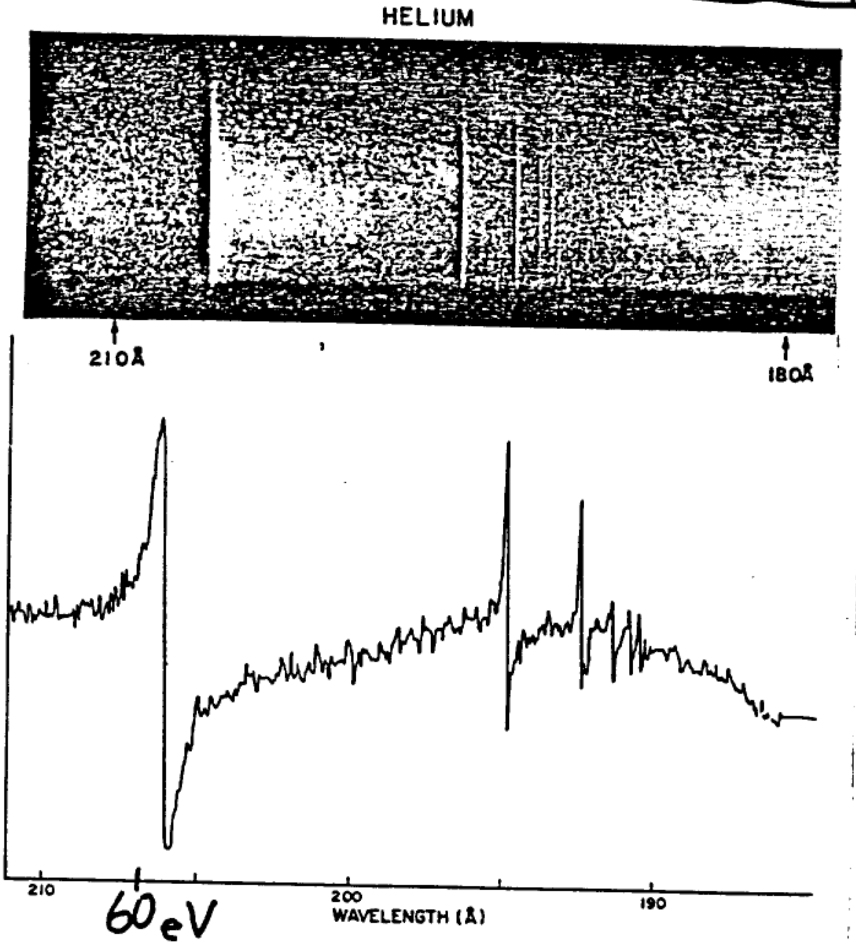
1963 Madden u. Codling

180 MeV Synchrotron, NBS; $\varepsilon_c = 17$ eV

Absorptionsspektren von Edelgasen

Autoionisation, Fano-Profil

He: $1s^2 \rightarrow 2snp$ oder $2pns$



1964 **DESY** 6 GeV (später 7.5 GeV) $\varepsilon_c = 50$ keV

Sy-Str.-Labor: Jentschke, Stähelin

Haensel: Röntgenstrahlen, fernes Vakuum UV

Skibowski u. Steinmann: nahes Vakuum UV

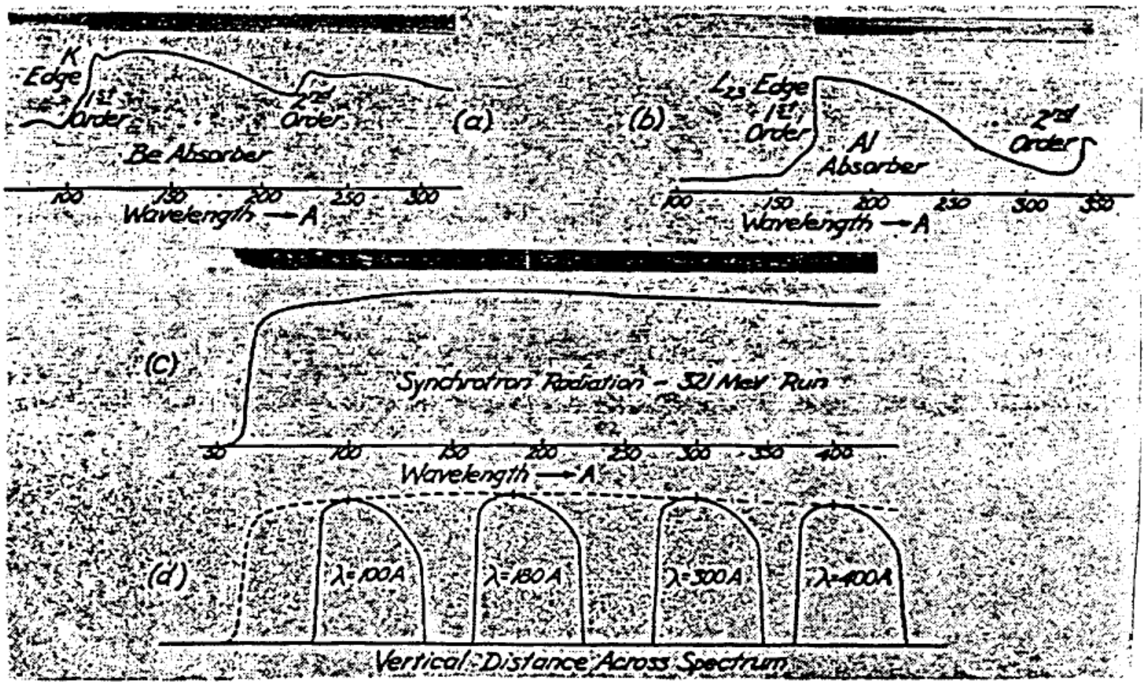
Spektroskopie

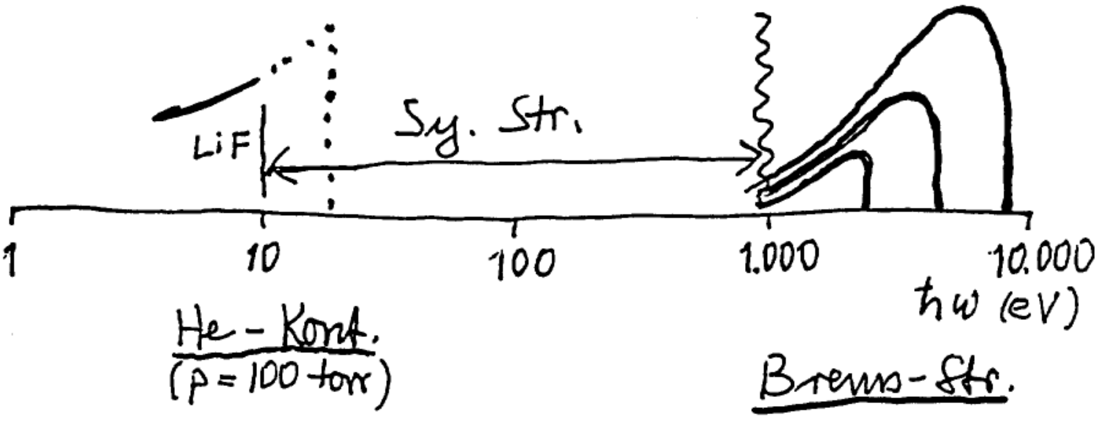
1953 Tomboulian u. Hartmann

300 MeV Synchrotron, Cornell ; $\varepsilon_c = 50\,\text{eV}$

Absorptionskanten: Al $L_{2,3}$: 73 eV

Be K : 113 eV





USE OF SYNCHROTRON RADIATION

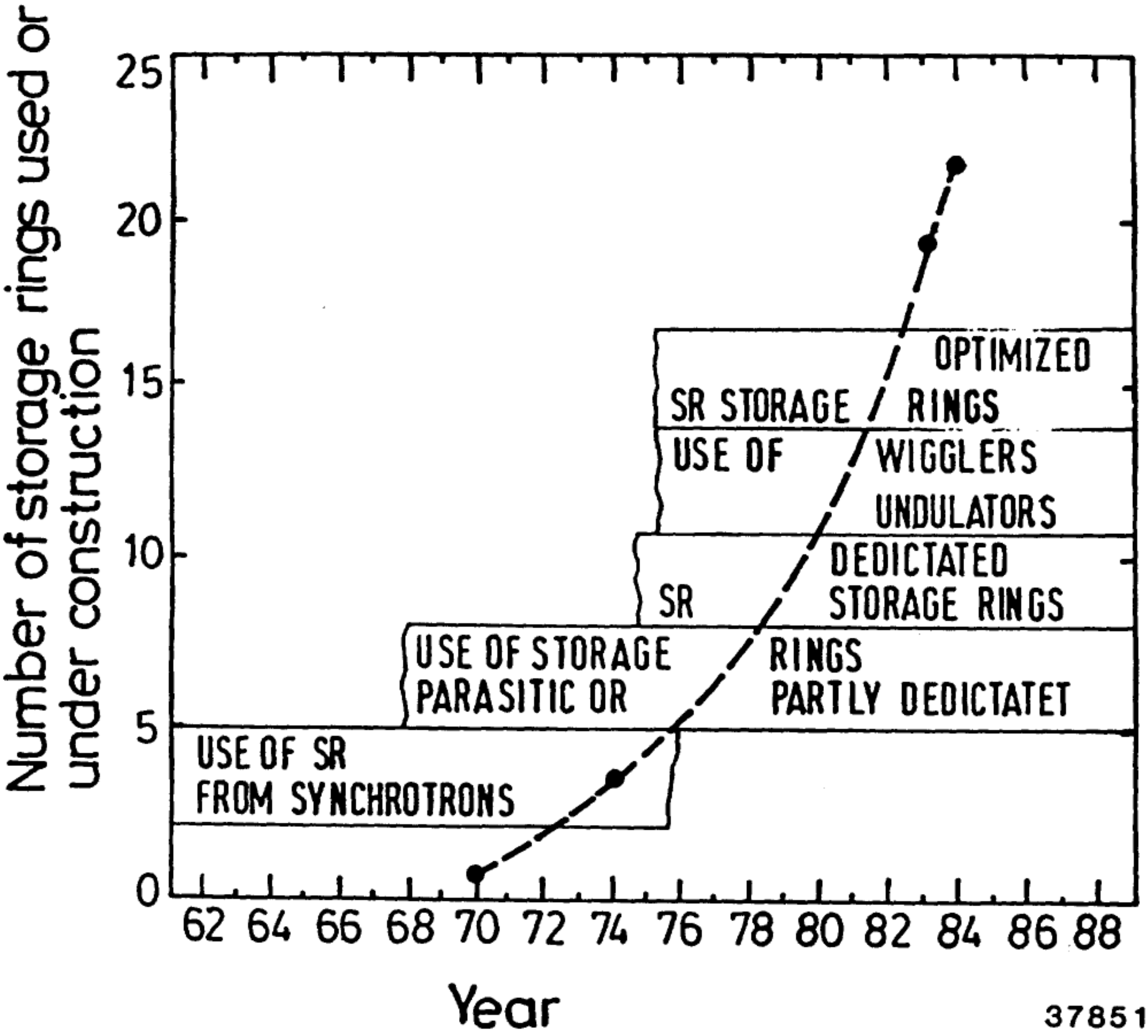
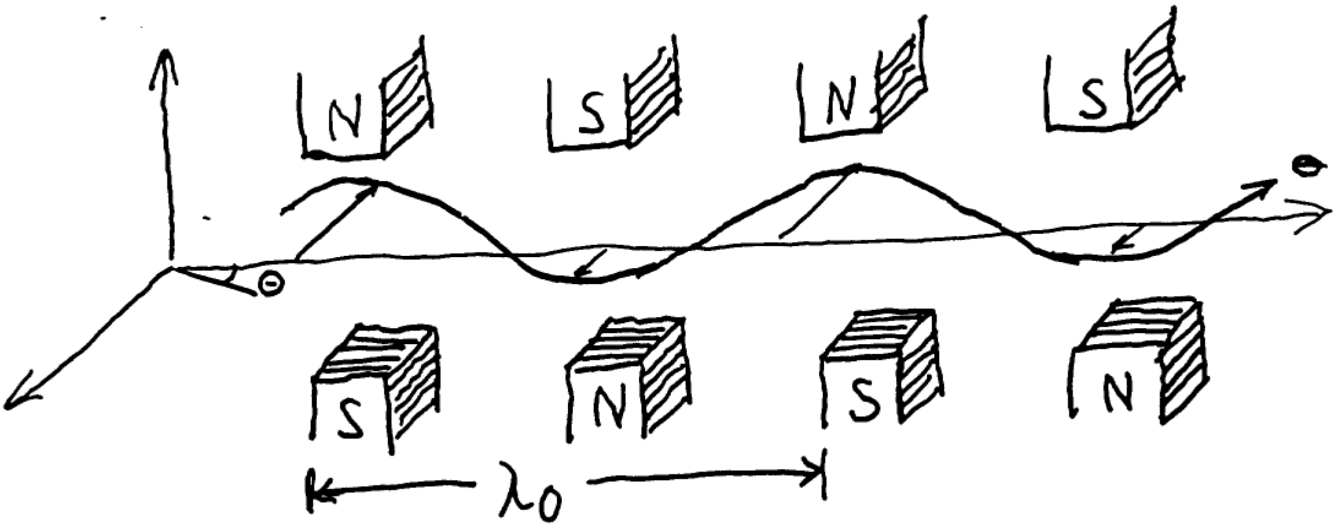


Fig. 2 This figure illustrates the various stages in the development of synchrotron radiation sources. Most of the early experiments were performed on synchrotrons and storage rings which had been built for particle physics experiments. Later the use of storage rings dedicated to the production of synchrotron radiation began. The use of wigglers and undulators and storage rings optimized to operate these devices is the latest stage in the rapid development. The increasing number of storage rings used for synchrotron radiation experiments also reflects the growing demand for these sources.

Undulator (Wiggler)



$$\lambda = \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

$$\gamma = \frac{E}{mc^2} \qquad K = \alpha B_0 \lambda_0$$

DORIS, 5 geV, 100 mA, $R_{DORIS} = 12\,m$

$N_{tot} = 4.5\,MW$, $N_{SySt} = 0.5\,MW$

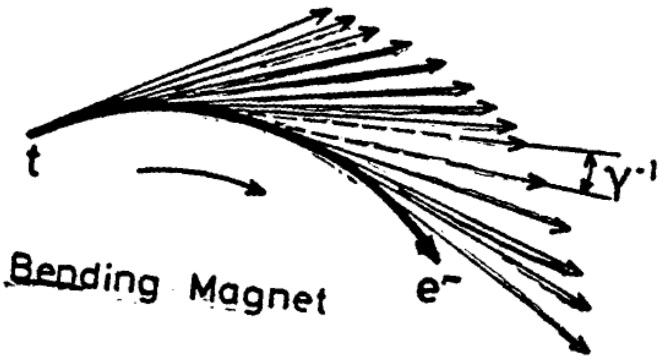
$$N_{SySt} \sim \frac{E^4}{R^2}$$

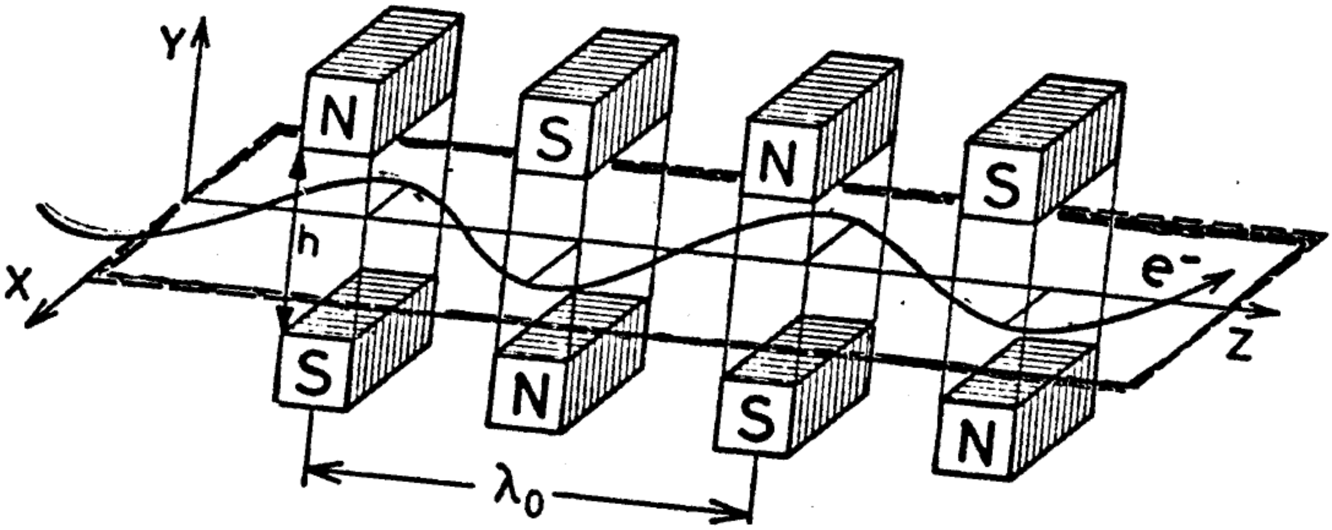
$$N_{tot} \sim N_{SyStr}$$

Europ. Sy. Rad. Facility

$R_{ESRF} = 48\,m$

$$N_{DORIS} = 16\,N_{ESRF}$$


t
γ^{-1}
Bending Magnet
e⁻


Y
N
S
N
S
h
X
e⁻
z
S
N
S
N
λ_0


Wiggler
e⁻
$(10\text{-}50)\gamma^{-1}$


Undulator
γ^{-1}

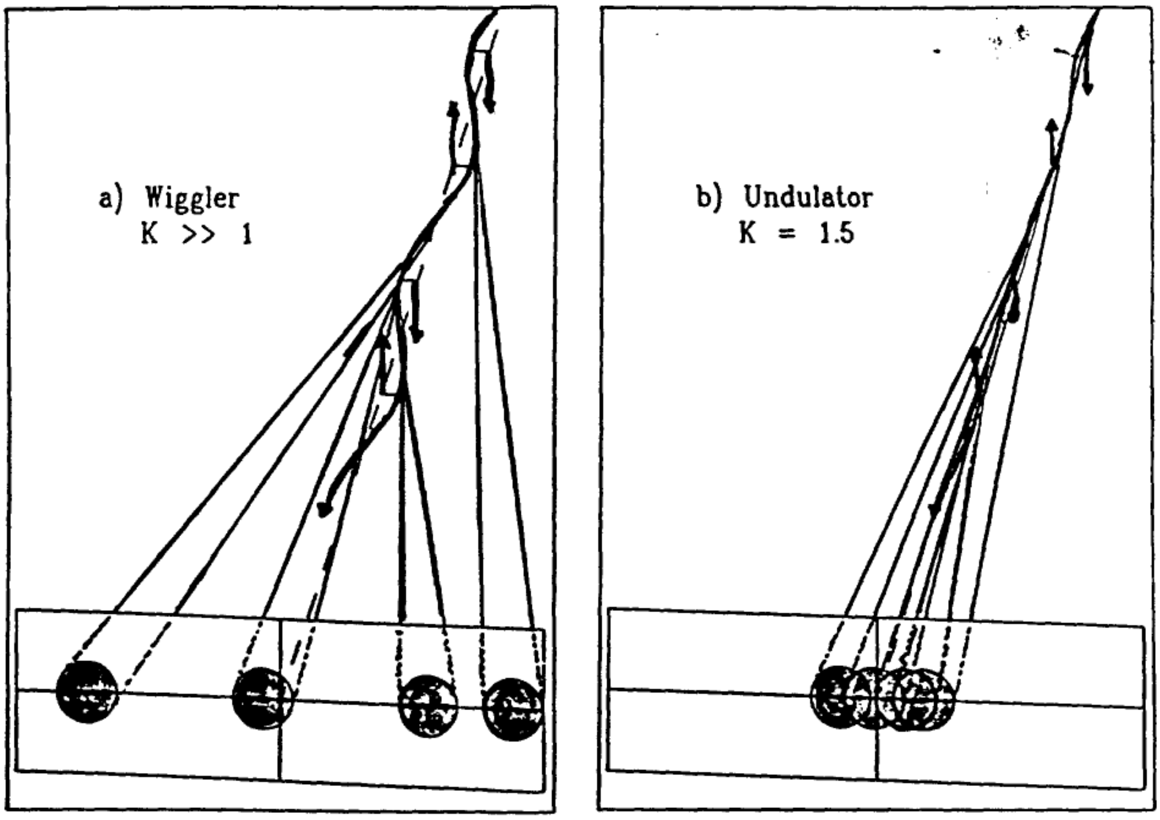


Abb.1:
Zum Prinzip von Wiggler und Undulator: Ein einzelnes Elektron emittiert bei einer transversalen Beschleunigung infolge eines Magnetfeldes Licht in einen engen Kegel (Scheinwerfereffekt der Synchrotronstrahlung infolge der relativistischen Elektronen-Energie). Vier solcher Strahlungskegel sind gezeichnet, die von der Elektronenbahn (dicke durchgezogene Linie) ausgehen und in einer Periode des Wigglers (a) bzw. Undulators (b) emittiert werden. Die Richtung des periodischen Magnetfeldes ist durch offene Pfeile angedeutet. In der Bildebene, die hier durch einen Schirm symbolisiert ist, gibt es im Wigglergrenzfall (a) nur geringes Überlappen der Strahlungskegel. Interferenzeffekte sind von untergeordneter Bedeutung und die Intensitäten addieren sich inkohärent. Für den Undulator (b) ist $K \approx 1$, und die Scheinwerferkegel überlappen. Die Intensitäten addieren sich kohärent und Interferenz führt zu einer räumlichen und zeitlichen Umverteilung der Intensität. In den Maxima des Undulatorspektrums ist die Brillanz gegenüber dem Wiggler-Grenzfall weiter erhöht (Undulator-Effekt).

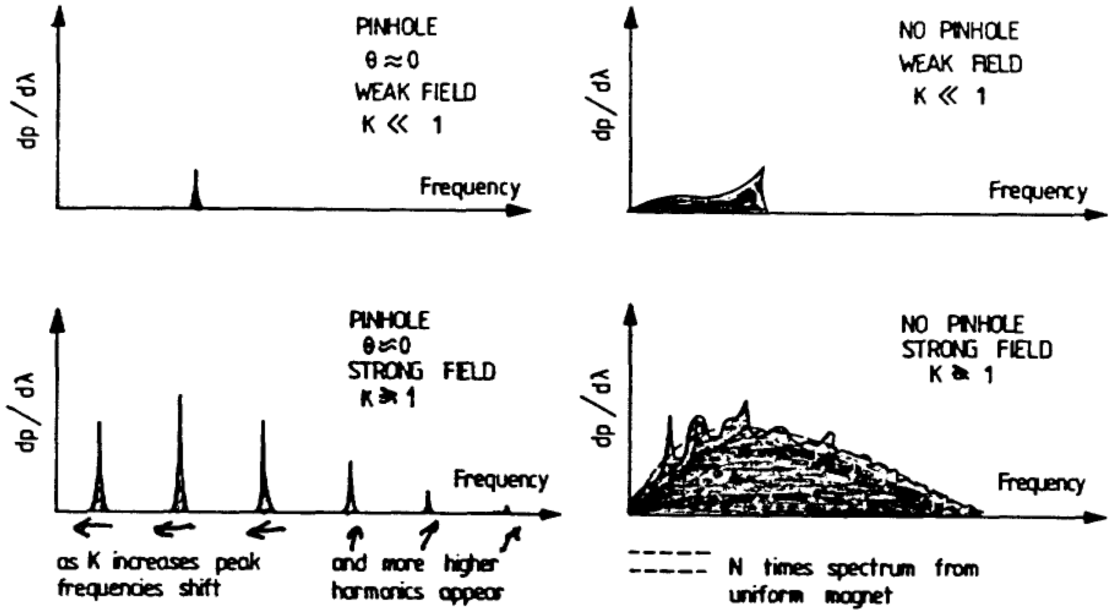
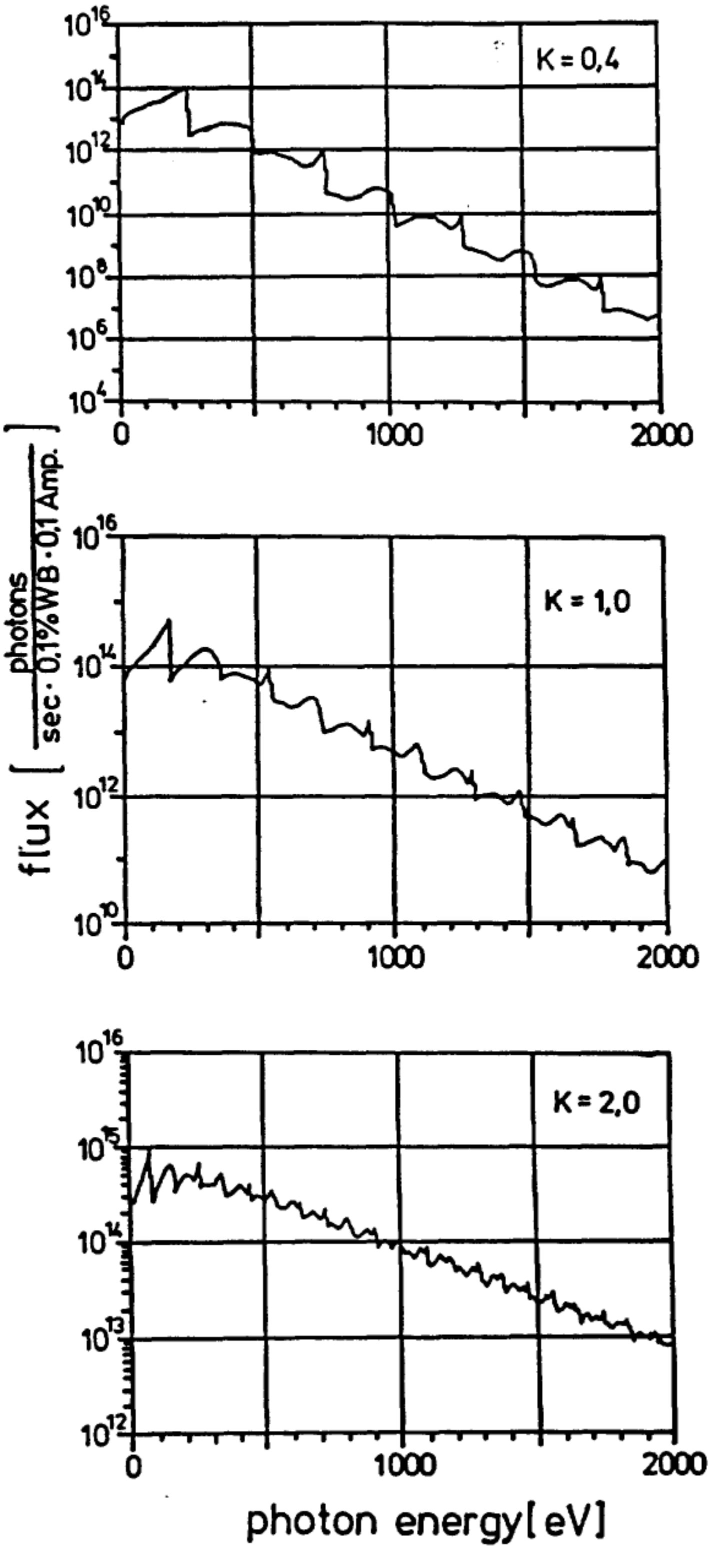


Fig. 2.6 Spectra from an undulator for (different) K on axis (pinhole) and integrated in the vertical and the horizontal plane (no pinhole). dp/dλ- power per unit wavelength.

It follows, however, from Eq. 2.14 that the width of the observed line is broadened relative to its natural value given by Eq. 2.16 due to the dependence of the wavelength on the observation angle. A further broadening may occur due to the divergence of the electron beam. A detailed discussion of these phenomena is given in Section 5.4.

In principle, a multipole wiggler can supply the same number of photons per second in the same bandwidth as an undulator in the fundamental. However, the opening angle of the radiation and the effective source size are greater, resulting in a smaller brightness and brilliance. Also, in the case of a multipole wiggler the first optical elements are exposed to a high total radiation power resulting from the unwanted as well as the wanted radiation. In the case of an undulator there is much less unwanted radiation, and radiation damage effects for a given useful flux are thus minimized. On the other hand, undulators are not suitable for all beam lines, because: it is difficult to design undulators for less than 1 Å radiation in the first harmonic (the ESRF is designed so that 0.86 Å can just be reached); the radiation is emitted in a very narrow cone and cannot easily be divided between two or more experiments; the wavelength is a function of angle; the radiation is less easily tunable or only tunable over a limited range.



<u>Abb. 2:</u> Der spektrale Fluß von Undulator U-2 in einen Winkel $\Theta = 2$ mrad (entsprechend $\gamma\Theta = 6$) für drei Wigglerstärken K (unterschiedlicher Maßstab!). Parameter: $N = 60$, $\lambda_o = 77$ mm, $\gamma = 2935$.

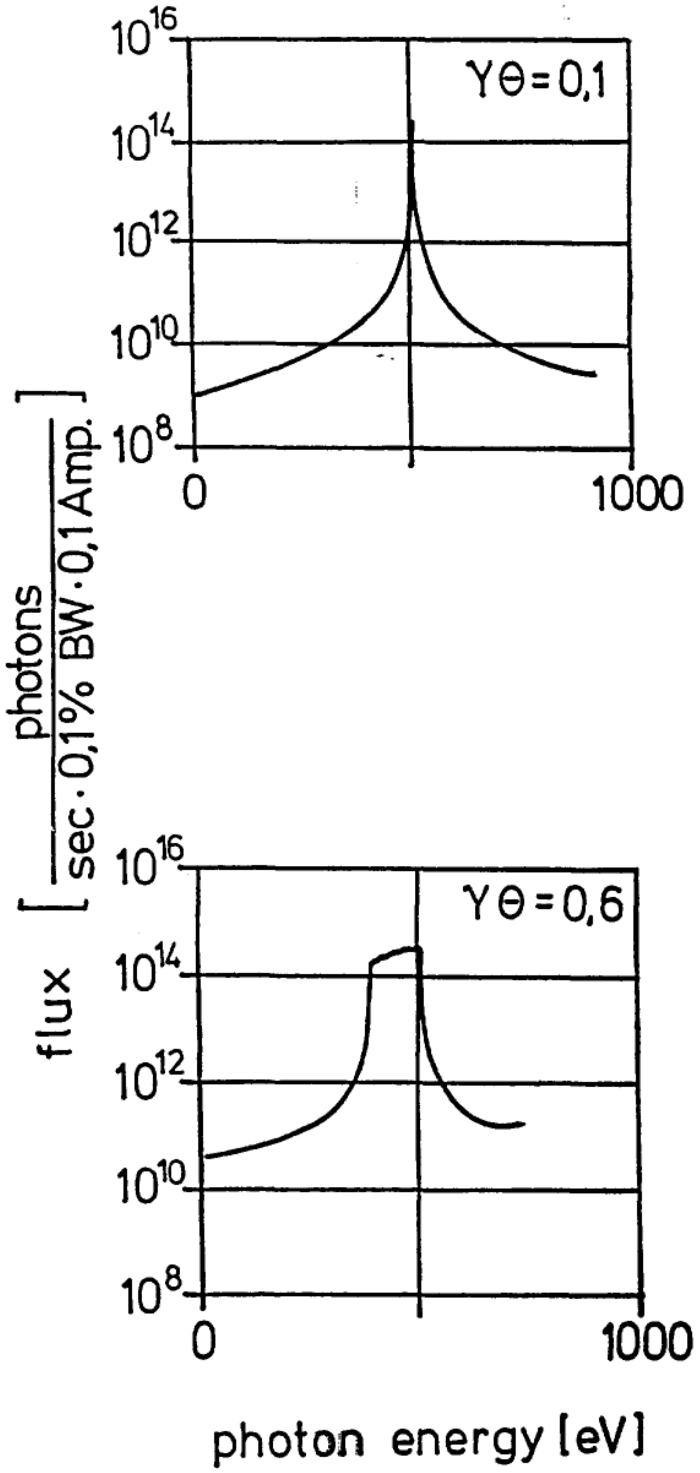


Abb. 3: Der spektrale Fluß des Undulators U-3 in einem Winkel $\theta = 33$ µrad (entspricht $\gamma\theta = 0,1$) bzw. $\theta = 200$ µrad (entspricht $\gamma\theta = 0,6$). Parameter: $N = 130$, $\lambda_o = 37$ mm, $\gamma = 2935$. Der größere Öffnugnswinkel verbreitert die Linien ohne sie zu erhöhen.

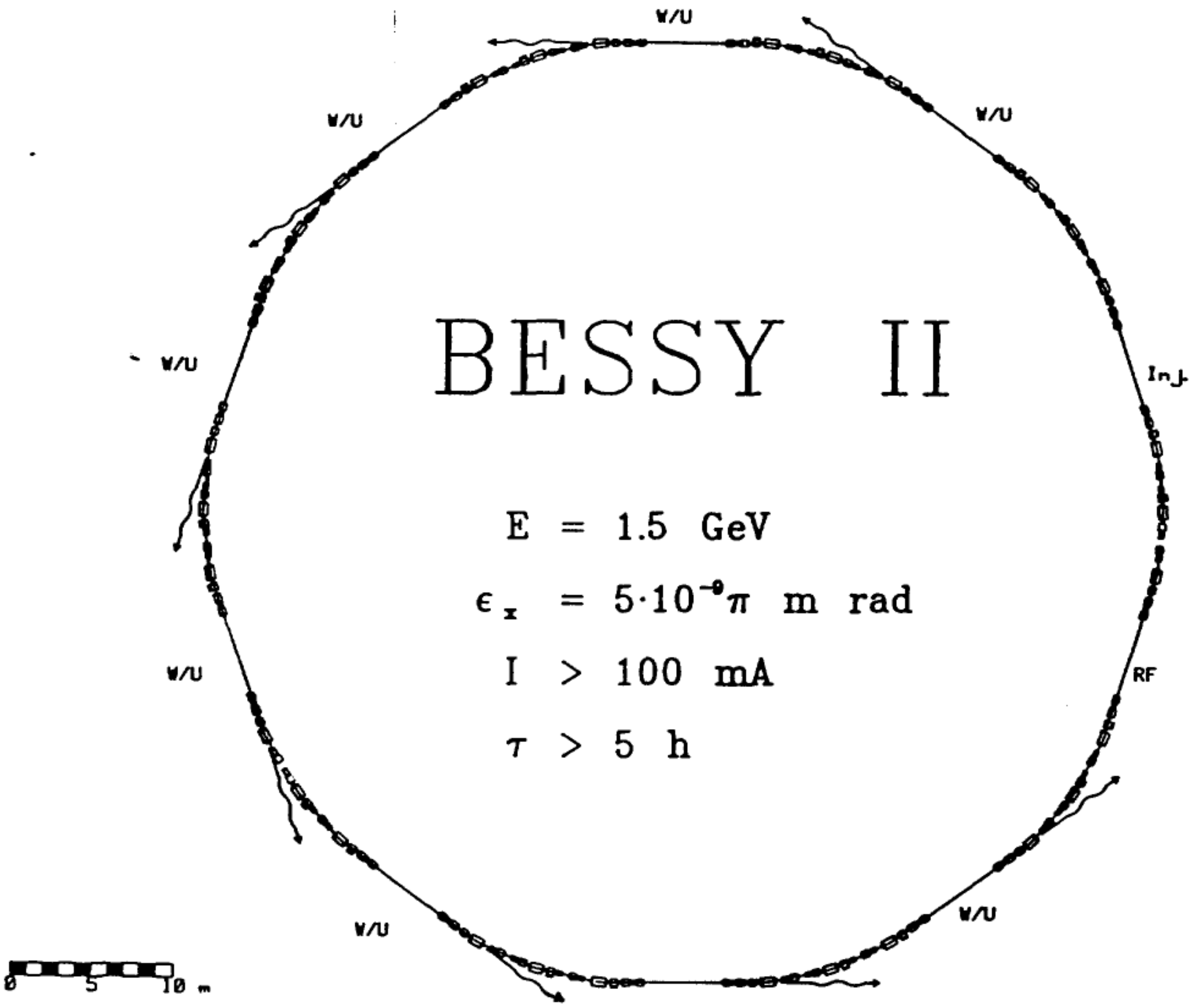


Abb. 1.5 a:
Der 1.5 GeV Elektronenspeicherring BESSY II hat einen Umfang von 182,4 m und einen mittleren Radius von 29 m. In dem insgesamt 10 geraden Stücken können 8 Wiggler und/oder Undulatoren gleichzeitig betrieben werden. Eine Gerade wird für die Injektoren, eine weitere für die Hochfrequenzbeschleunigungs-Strecke benötigt.

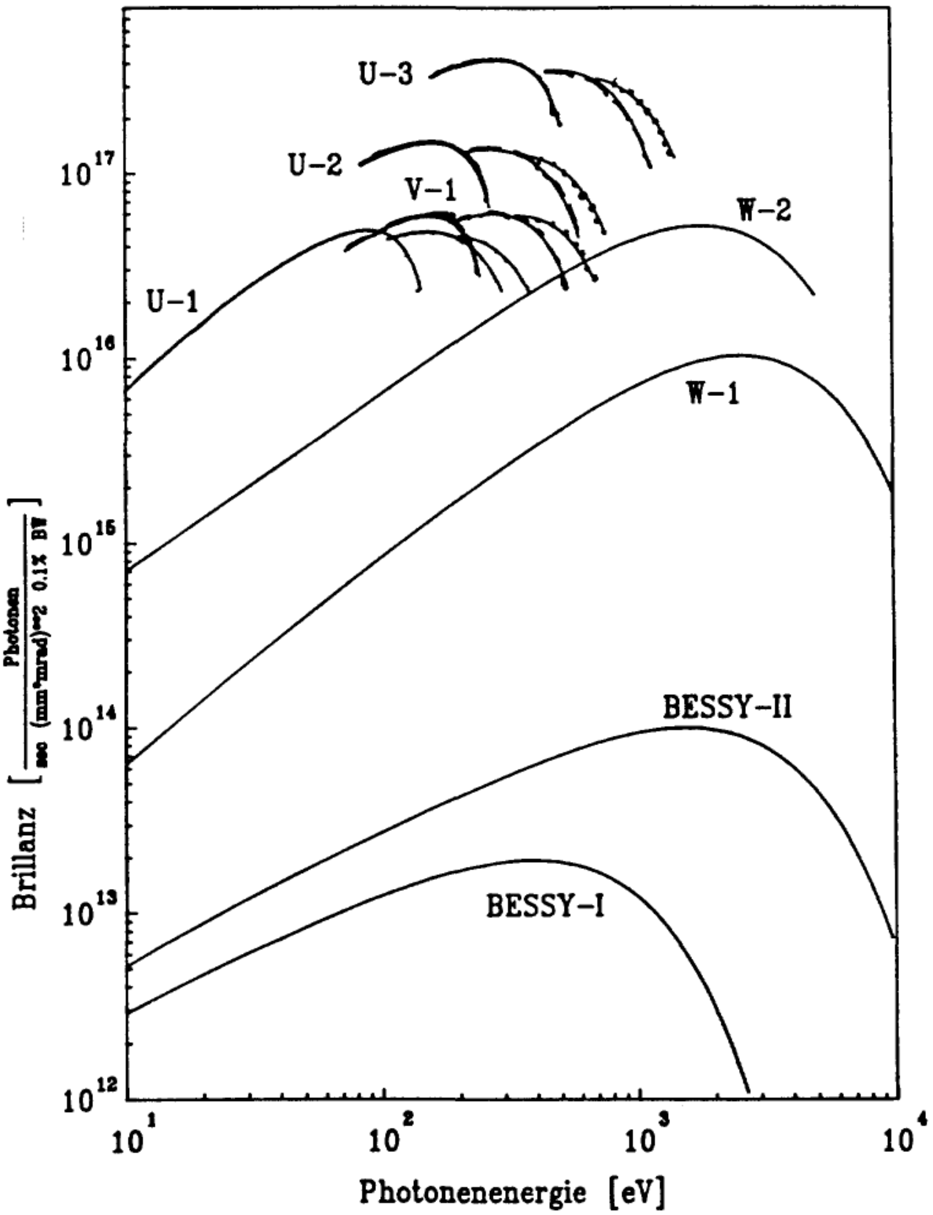
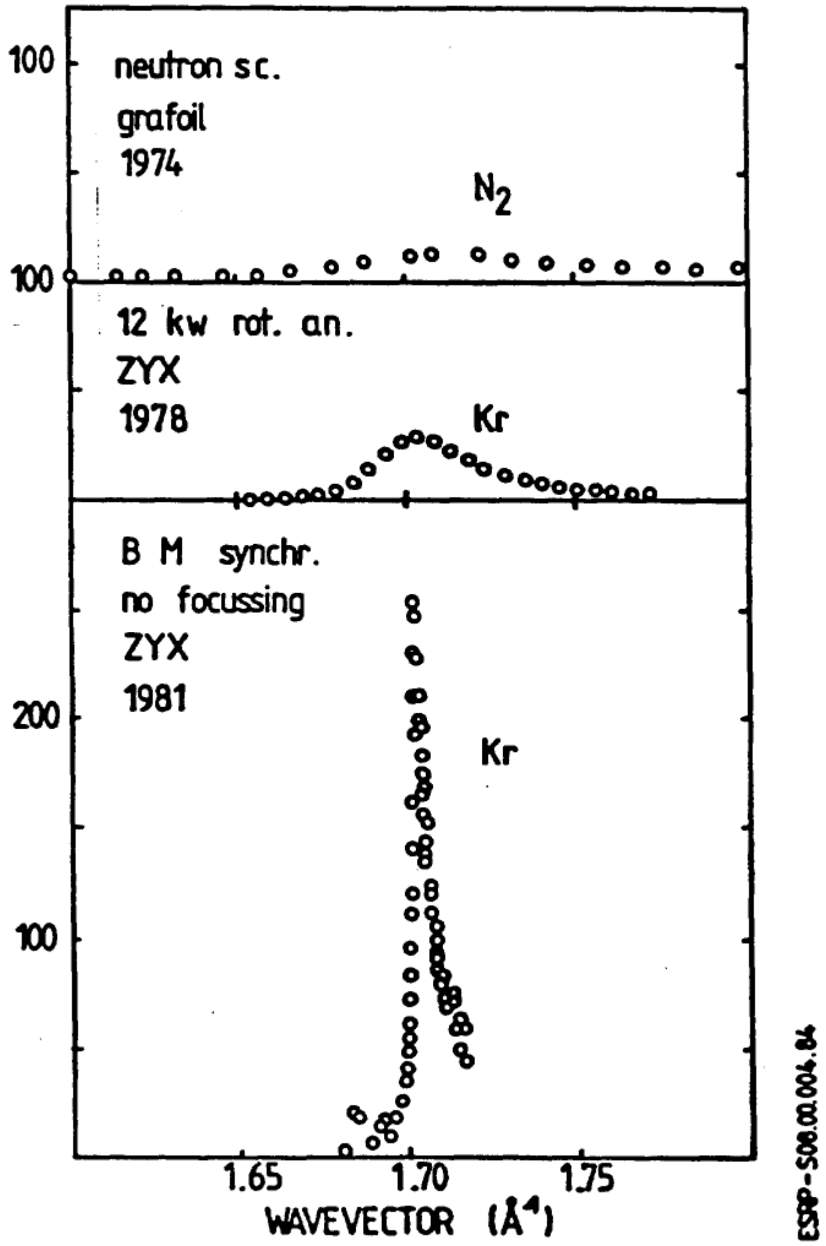


Abb. 1.3:

Brillanz auf der Strahlachse für die Undulatoren (Durchstimmkurven jeweils erste, dritte und fünfte Ordnung) und Wiggler im Vergleich zur Strahlung aus den Ablenkmagneten von BESSY II und BESSY I. Zugrunde liegen folgende Parameter für den Speicherring BESSY II:

$E = 1{,}5$ GeV, $\varepsilon_x = 5 \cdot 10^{-9}$ $\pi \cdot$m$\cdot$rad, $\varepsilon_y = 0{,}5 \cdot 10^{-9}$ $\pi \cdot$m$\cdot$rad, I = 100 mA,
$\rho = 3{,}83$ m, $\varepsilon_C = 1{,}95$ keV, $\beta_x = 1{,}5$ m/rad, $\beta_y = 12$ m/rad, I = 100 mA
Die Kenngrößen für die Undulatoren und den Wiggler werden im Abschnitt 3.2 beschrieben.(BESSY I: E = 750 MeV, I = 300 mA)



<u>Figure 1</u> Diffraction profiles of the (1,0) reflection of a registered $\sqrt{3} \times \sqrt{3}$ mono-atomic film on graphite. The data from ref. 1 and and 2 have been scaled so all peaks appear with the same area.

<u>Top</u>: Neutron data of N_2 on grafoil (from ref. 1)

<u>Centre</u>: 10 kW rotating anode X-ray data of Kr on ZYX graphite (from (3))

<u>Bottom</u>: Same sample as central panel, but using synchrotron radiation from a bending magnet without focussing devices (from (4-5)).

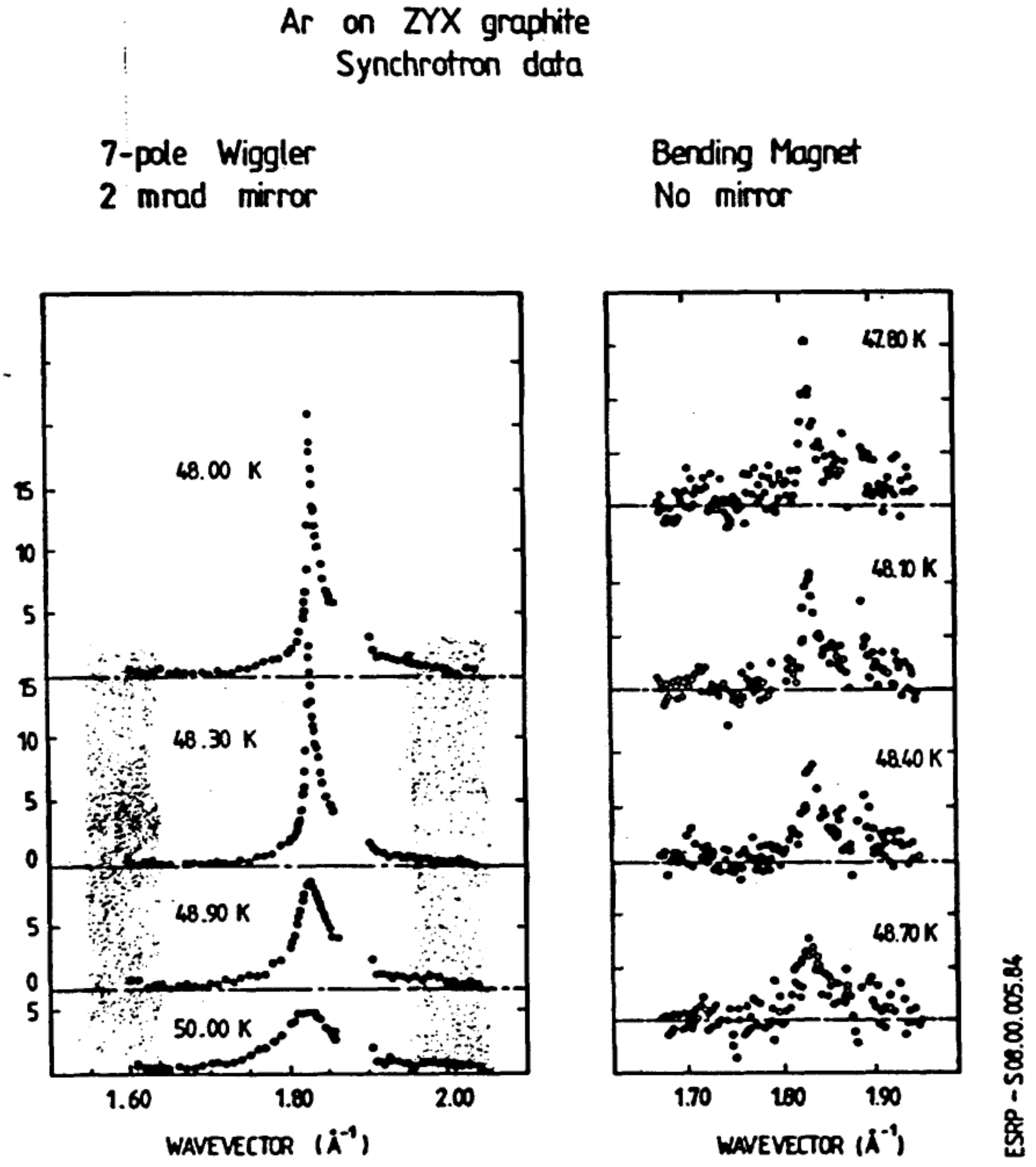
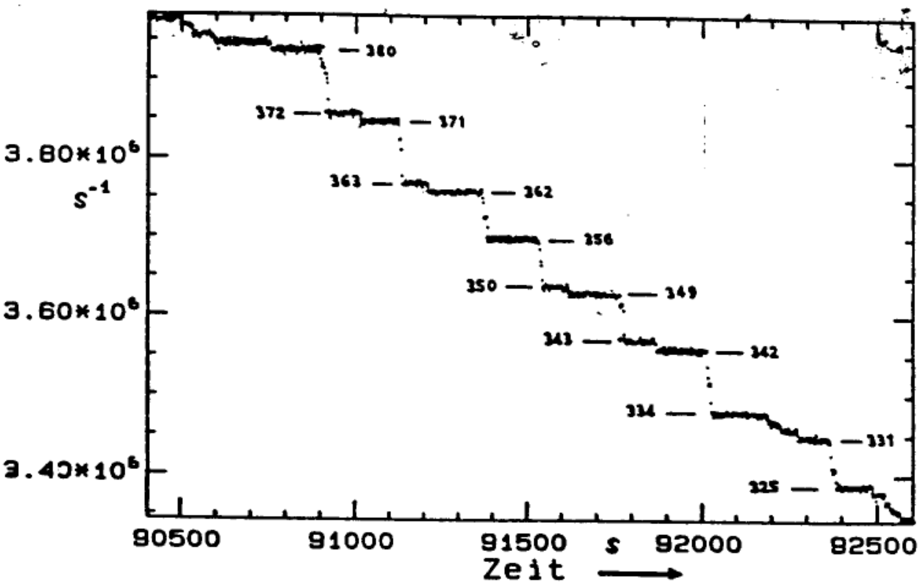


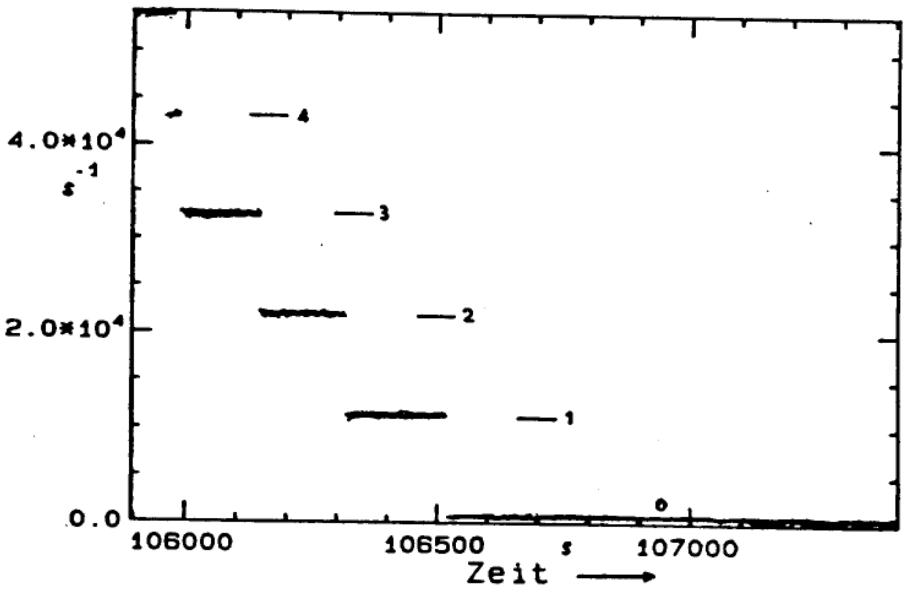
Figure 2 Melting of two-dimensional Ar on ZYX graphite. The solid phase is incommensurate with the underlying graphite substrate lattice.

Right: Synchrotron source equivalent to that for bottom part of Fig. 1.

Left: 7-pole wiggler, 2 mrad focussed synchrotron radiation



a)



b)

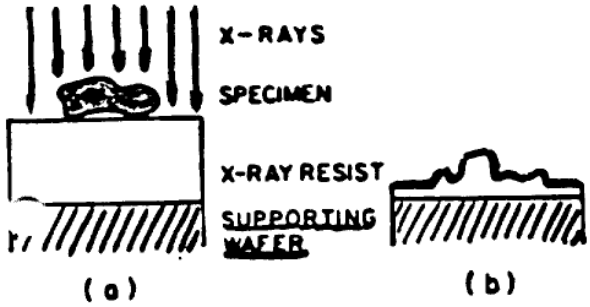
Abb. 2

Photonenzählraten für abklingenden Ringstrom von BESSY I

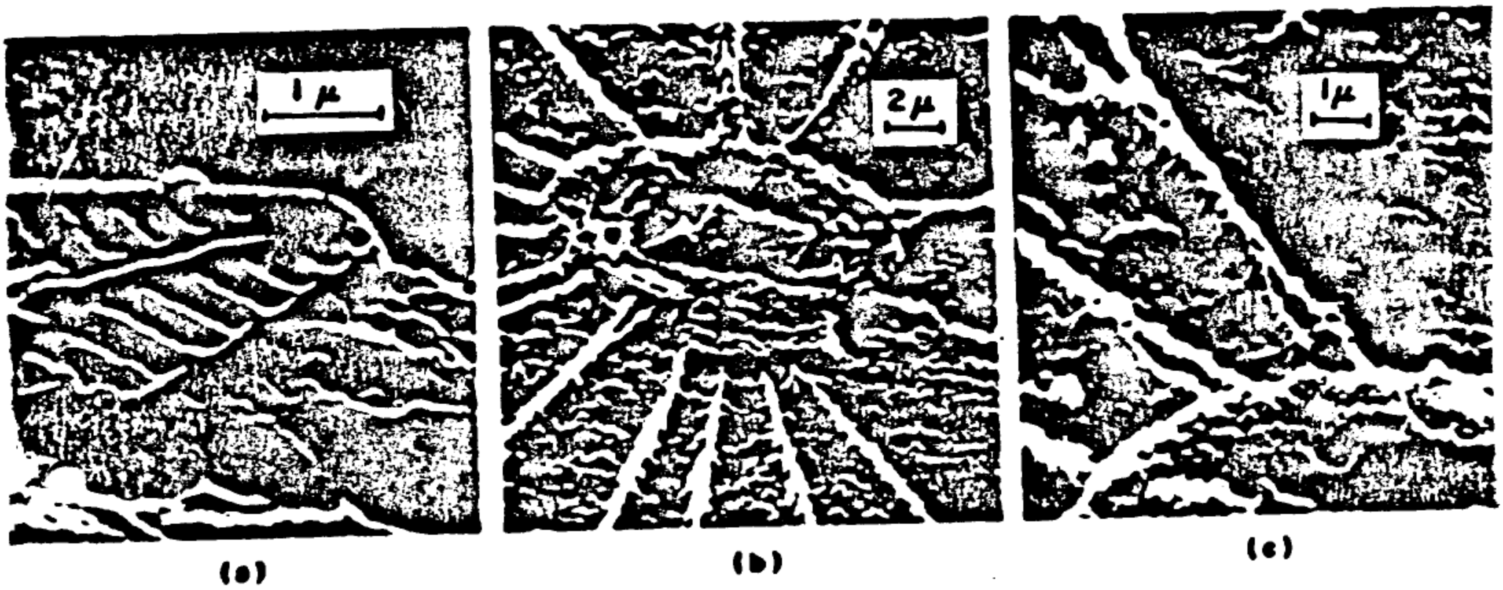
a) bei ca. 350 verbliebenen Elektronen

b) bei 5 bis 1 verbliebenen Elektronen

SR SOFT X-RAY CONTACT MICROSCOPY



Principle of X-ray micrography. (a) Irradiation of the X-ray resist through th specimen. In X-ray lithography, the specimen is a mask generated by an electron beam (b) the replica after development of the resist (from Ref. [142]*).*



(a) (b) (c)

FIG.34. X-ray replicas of diatoms obtained with synchrotron radiation; (c) is a detail of (b) (from Ref. [143]*).*

SPILLER, FEDER, TOPALIAN, EASTMAN, GUDAT, SAYER

SCIENCE 191 1172 (1976)

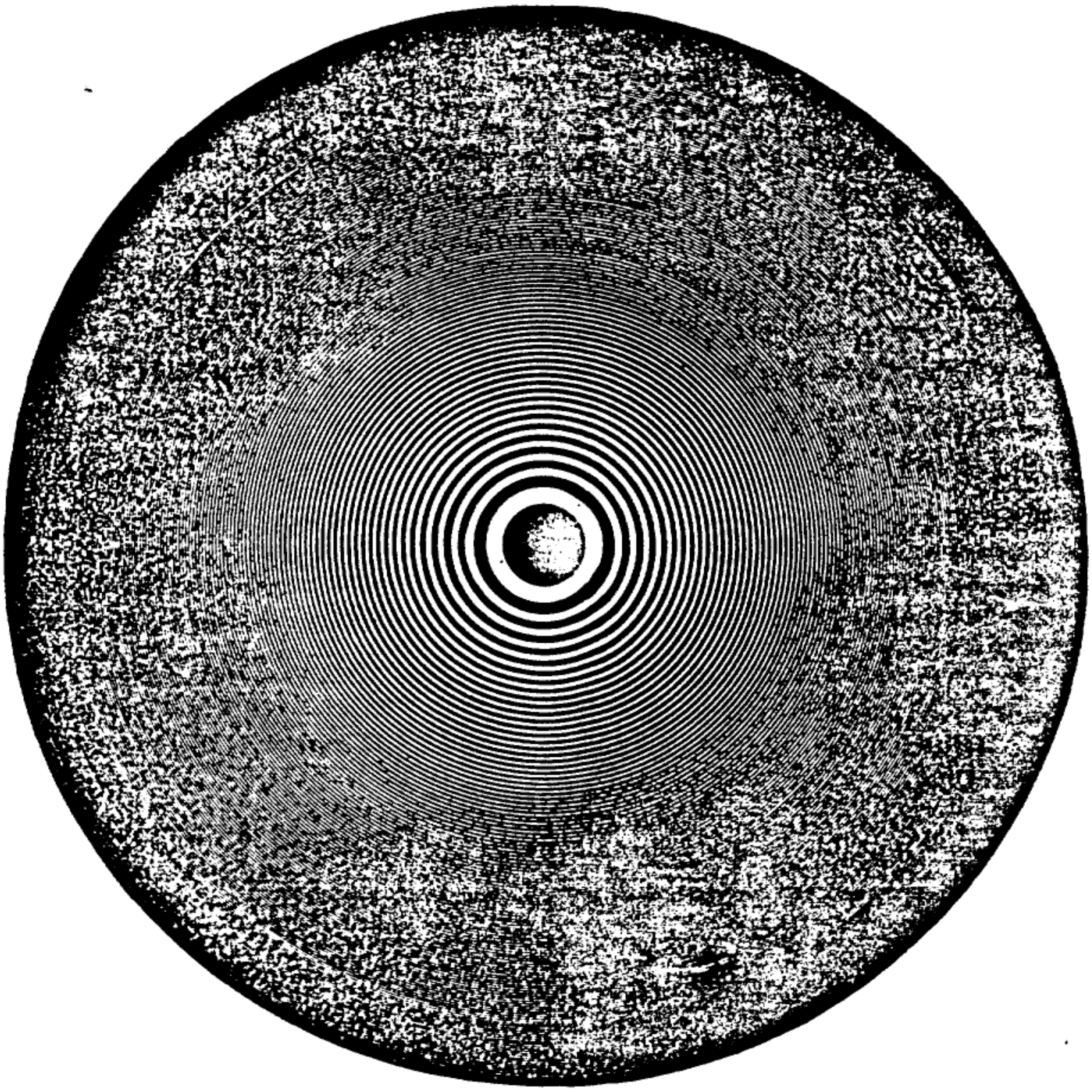
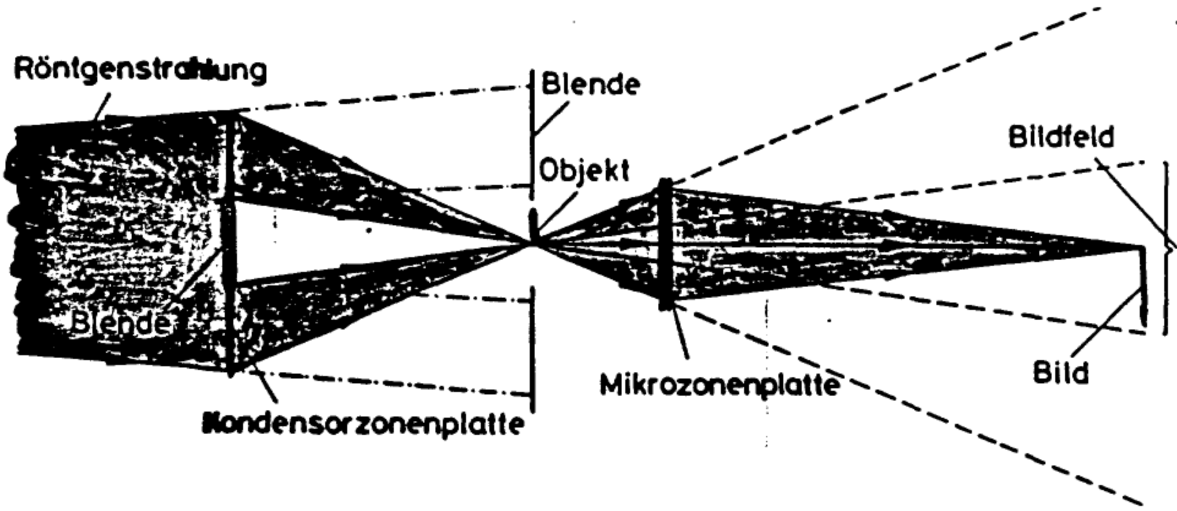


PLATE 2. ZONE-PLATE, FROM A DRAWING.



Strahlengang im Röntgenmikroskop:

Vom Elektronenspeicherring emittierte Röntgenstrahlung wird vom Kondensor auf das Objekt fokussiert, das sich auf einer kleinen Blende befindet. Kondensor und Blende wirken dabei zusammen als Linearmonochromator. Das Objekt wird mit Hilfe einer hochauflösenden Röntgenlinse (Mikrozonenplatte) vergrößert in die Bildebene abgebildet und dort auf einem Bildwandler sichtbar gemacht oder direkt photographiert

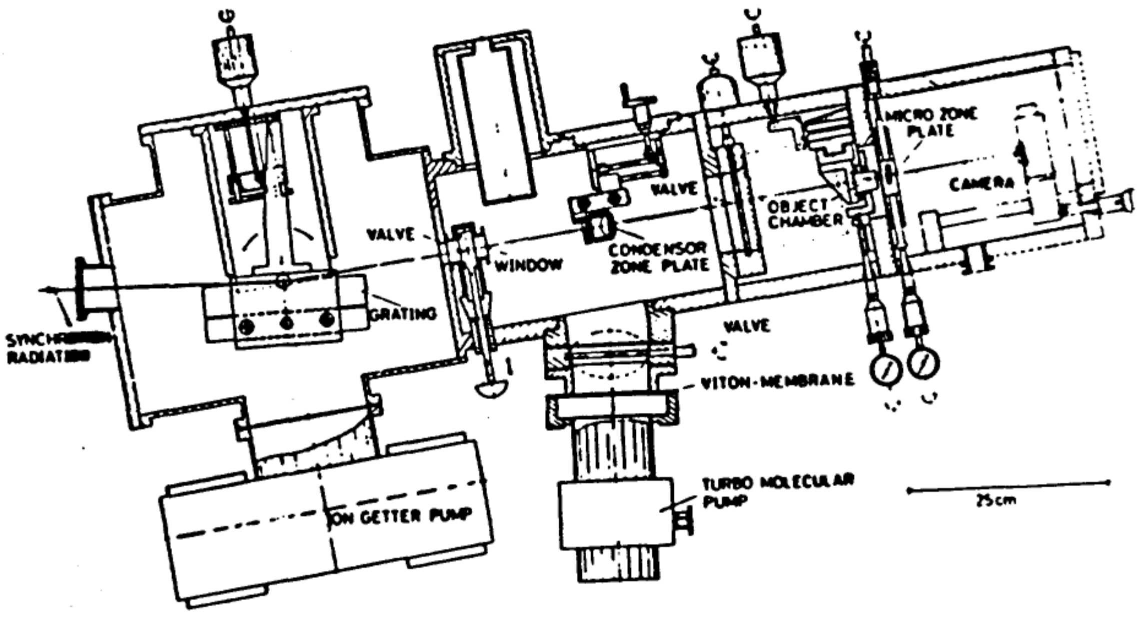


Fig. 19. Zone plate microscope at the ACO storage ring in Orsay (Schmahl et al. 19

Abb. 2.14:

Das Bild zeigt einen Ausschnitt einer menschlichen Bindegewebszelle und wurde am Elektronenspeicherring BESSY I mit dem Göttinger Röntgenmikroskop aufgenommen. Für die Aufnahme wurde Röntgenstrahlung der Wellenlänge $\lambda = 4{,}5$ Nanometer benutzt. Die Belichtungszeit betrug 4 Sekunden, die Auflösung beträgt etwa 50 Nanometer. Die Zelle ist nach der kritischen Punkt-Methode getrocknet und wurde von Dr. P. C. Cheng, USA, zur Verfügung gestellt.

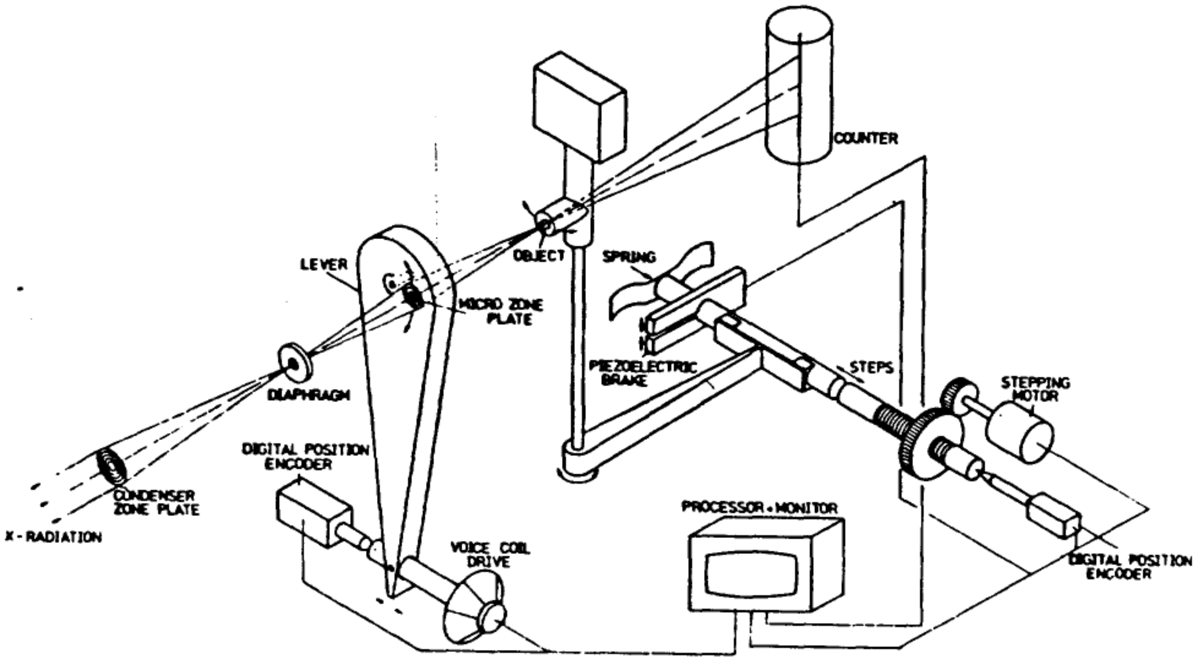


Fig. 6.14 Schematic of a scanning X-ray microscope

For scanning X-ray microscopy a **tunable undulator** at a storage ring with 2.5 GeV < E < 5 GeV is the ideal X-ray source because in a scanning X-ray microscope only the radiation concentrated in a very small collection angle can be used. It is essential that the power reaching the first optical element is not too high. Therefore the smaller the bandwidth of the radiation emitted by the undulator, the better. A reduction of the power reaching the first optical element - without a reduction of the photon density in the scanning spot - can be achieved by using a cooled 100 μm pinhole installed in the storage ring near the undulator.

For an undulator with a period of 28 cm, an electron energy of 5 GeV, 18 periods, a K-value of 1.5, an electron current of 100 mA, a source size of about 1 mm x 0.2 mm, and a pin-hole of 0.1 mm diameter we will get about 10^9 - 10^{10} photons/s in the scanning spot of 10 nm, assuming a spectral bandwidth of 0.2 % and zone plate diffraction efficiencies of about 10 %. Such photon densities are necessary when examining features with low inherent contrast. For comparison: A scanning X-ray microscope at a bending magnet of a 0.8 GeV storage ring with a source size of 0.2 mm x 0.2 mm, a pin-hole of 0.1 mm diameter and a current of 100 mA results in about 10^6 photons/s in a scanning spot of 10 nm diameter.

In the scanning X-ray microscope a differential pumping system is needed in front of the linear monochromator which will work in a vacuum of

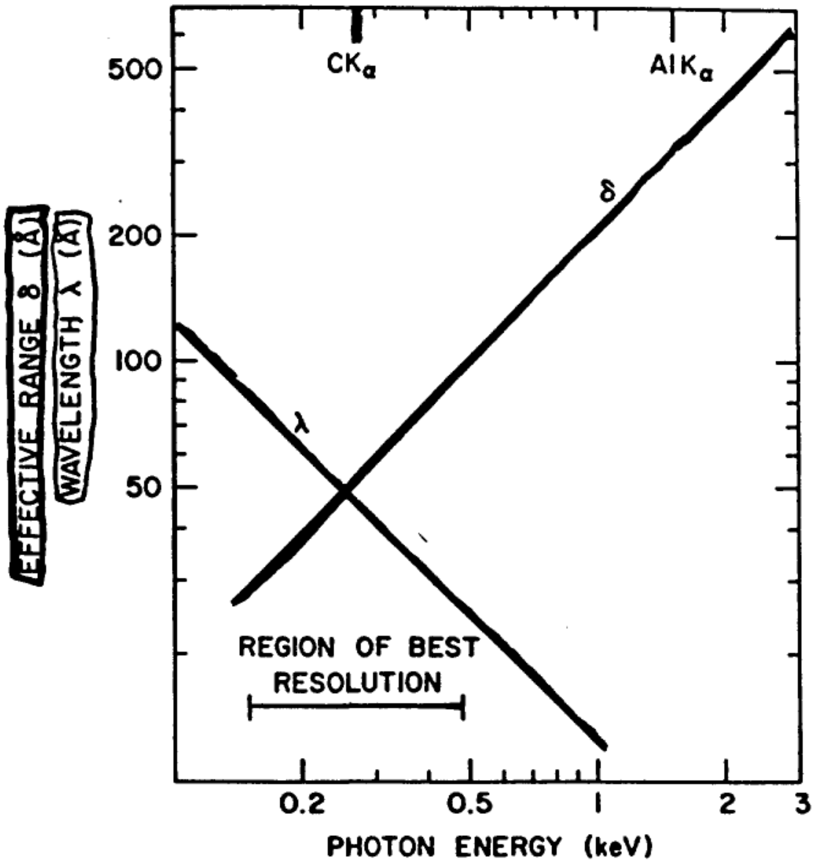


Fig. 14. Effective range of secondary electrons generated by X-rays in PMMA versus the photon energy. Best resolution is obtained where this range is in the order of the X-ray wavelength.

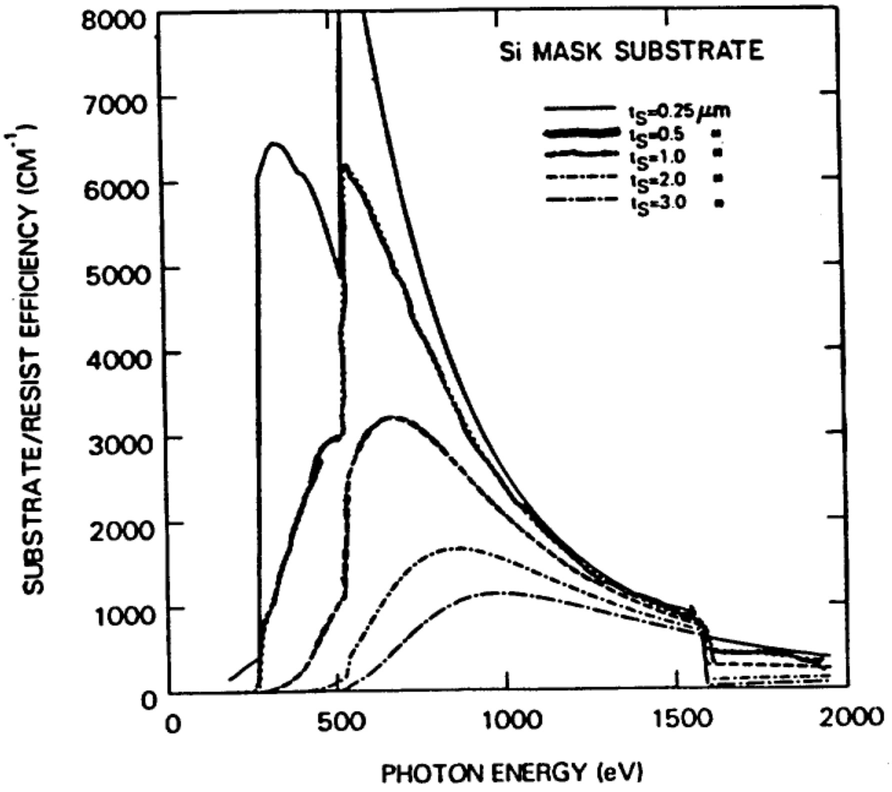


Fig. 10. The lithographic efficiency $\varepsilon(h\nu)$ for Si mask substrates of 0.25, 0.5, 1.0, 2.0, and 3.0 μm thickness and for PMMA resist. This quantity is simply interpreted as the power absorbed per unit volume of resist per unit incident flux (power per square cm incident on the mask).

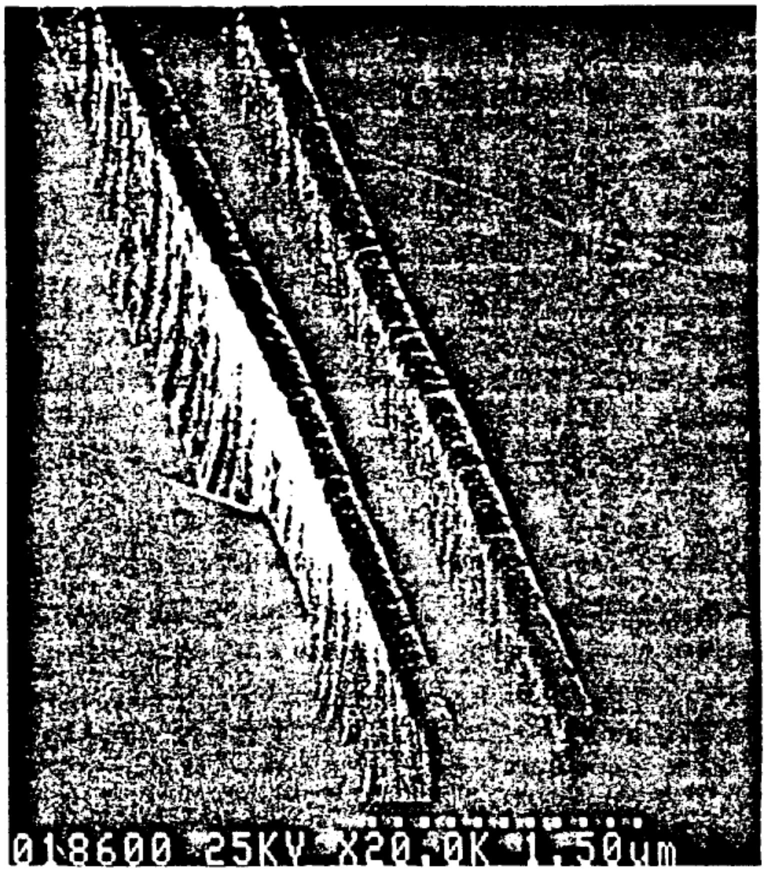


Abb. 2.16:
Eine am BESSY I röntgenlithographisch hergestellte Resiststruktur. Die Abbildung zeigt zwei Resistbahnen eines Novolak-Systems auf einem vorstrukturierten Silizium/Siliziumdioxid-Substrat. Sie besitzen eine Breite von ca. 0,15 µm und eine Höhe von 1,5 µm. Die besondere Eignung der Synchrotronstrahlung für lithographische Anwendungen zeigt sich unter anderem in der von der Wafer-Topographie unabhängigen Linienbreite. In diesem Beispiel werden die Resistprofile von den kreuzenden SiO_2-Bahnen nicht beeinflußt. Bild: Fraunhofer-Institut für Mikrostrukturtechnik (IMT), Berlin.

SOURCE : Bessy 754 MeV RESIST THICKNESS : 1.5 µm GOLD THICKNESS : 1.0 µm

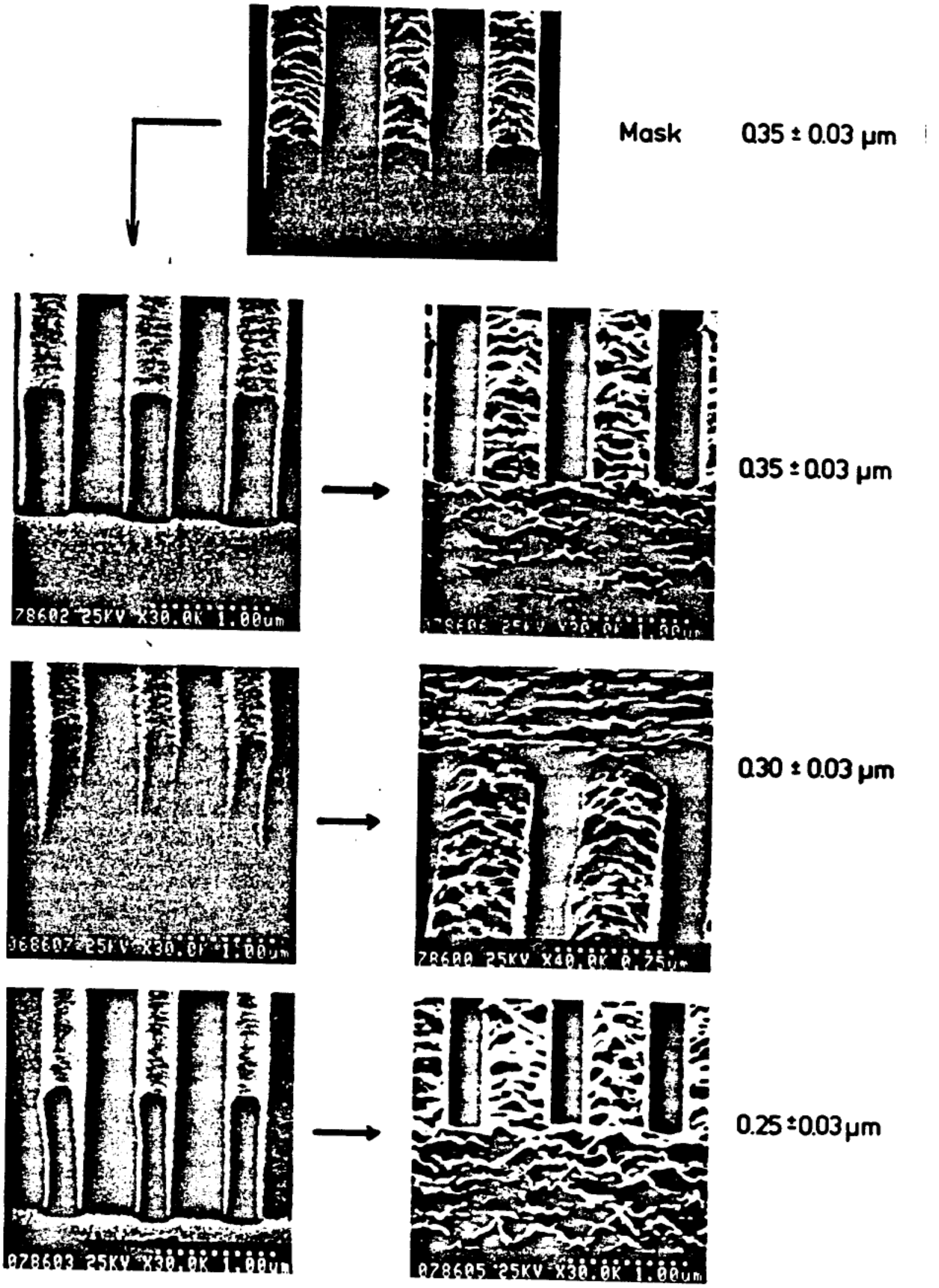


Abb. 4: Beherrschbarkeit der kritischen Dimension bei der Maskenkopie durch gezielte Einstellung der Linienbreite.

nach metallischer Bedampfung ein pilzförmiges Gate entstehen läßt (T-Gate). Ein für diesen Metallisierungsprozeß gut geeignetes typisches Resistprofil ist in der REM-Aufnahme der Abb. 13 zu sehen.

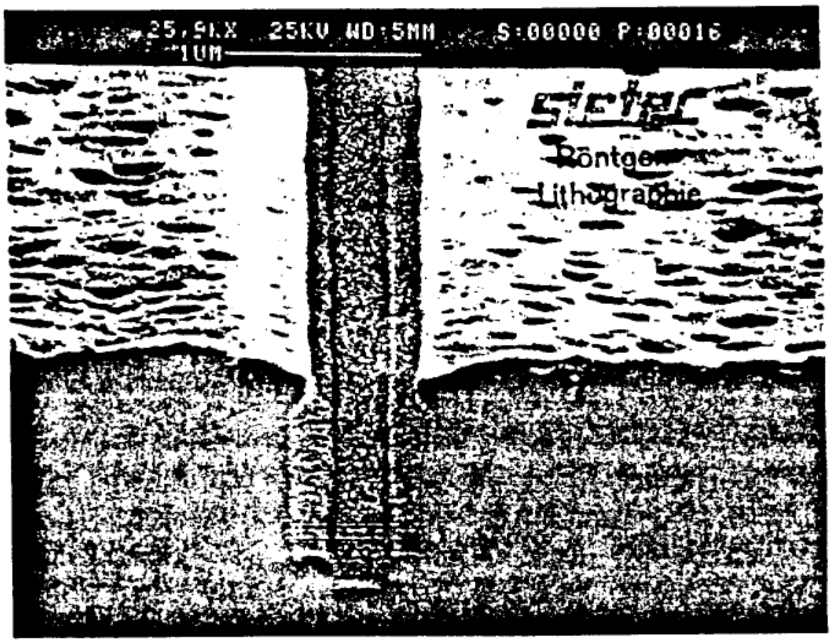


Abb. 13: Röntgenlithographisch hergestellter 0,3 µm breiter Gategraben in PMMA für Galliumarsenid-FETs

Bei ersten erfolgreich prozessierten Labormustern handelt es sich um Transistoren mit einer Gatelänge von 0,45 µm, die in der bekannten Siemens-Planartechnik hergestellt wurden. Diese ersten mit Hilfe der Röntgenstrahllithographie hergestellten FETs sind im Gleichstrom und Kleinsignalverhalten konventionellen Halbmikron-FETs vergleichbar und zeigten eine minimale Rauschzahl von < 2,0 dB bei 12 GHz.

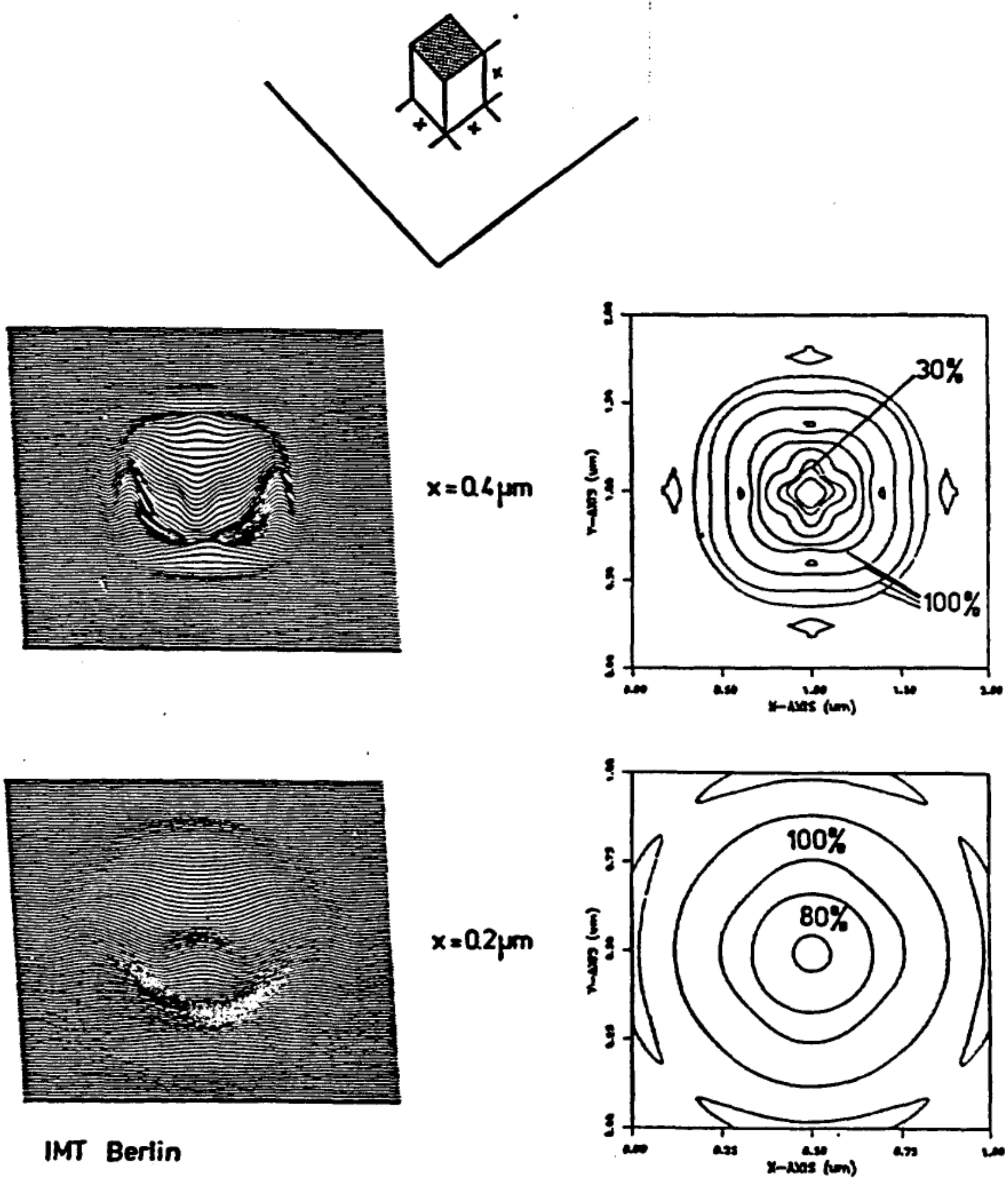
Diese ersten Ergebnisse entsprechen den Erwartungen, insbesondere wurde kein negativer Einfluß der Röntgenlithographie auf das FET-Verhalten festgestellt. Die angestrebten Ziele eines neuen Sub-Halbmikron-FETs mit einer Rauschzahl < 1,6 db bei 12 GHz sollten durch die in der Entwick-

Exposure conditions: BESSY 754 MeV

Beamline 1.22 µm Si, 10 µm Be, 1000 µm Air

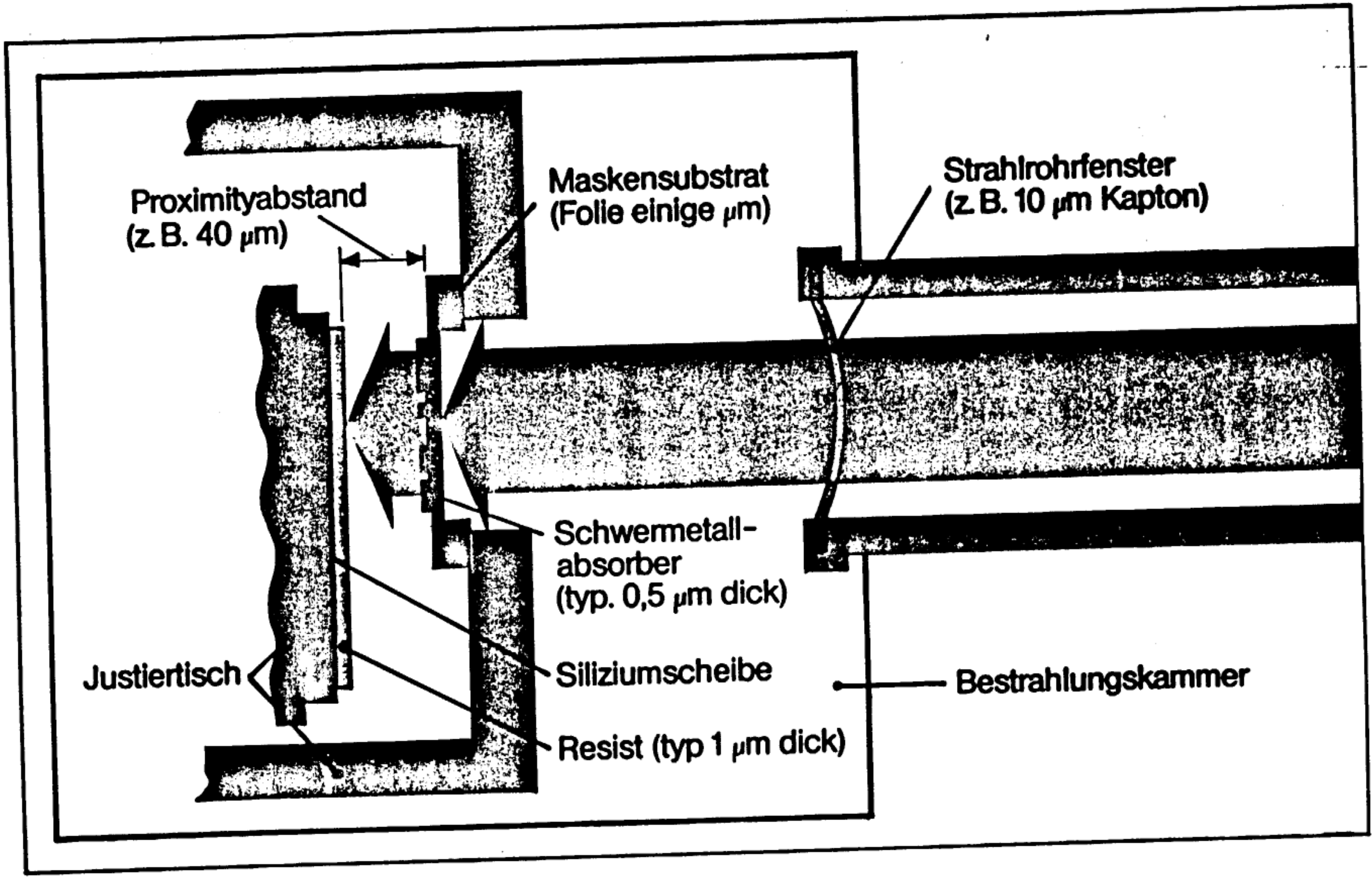
Resist 1µm PMMA Proximity gap 50 µm

PARTICLE GEOMETRY:



IMT Berlin

Abb. 12: Übertragung von Eisenpartikeln bei der Lithographie mit Synchrotronstrahlung


Proximityabstand
(z.B. 40 µm)
Maskensubstrat
(Folie einige µm)
Strahlrohrfenster
(z.B. 10 µm Kapton)
Schwermetall-
absorber
(typ. 0,5 µm dick)
Justiertisch
Siliziumscheibe
Bestrahlungskammer
Resist (typ 1 µm dick)

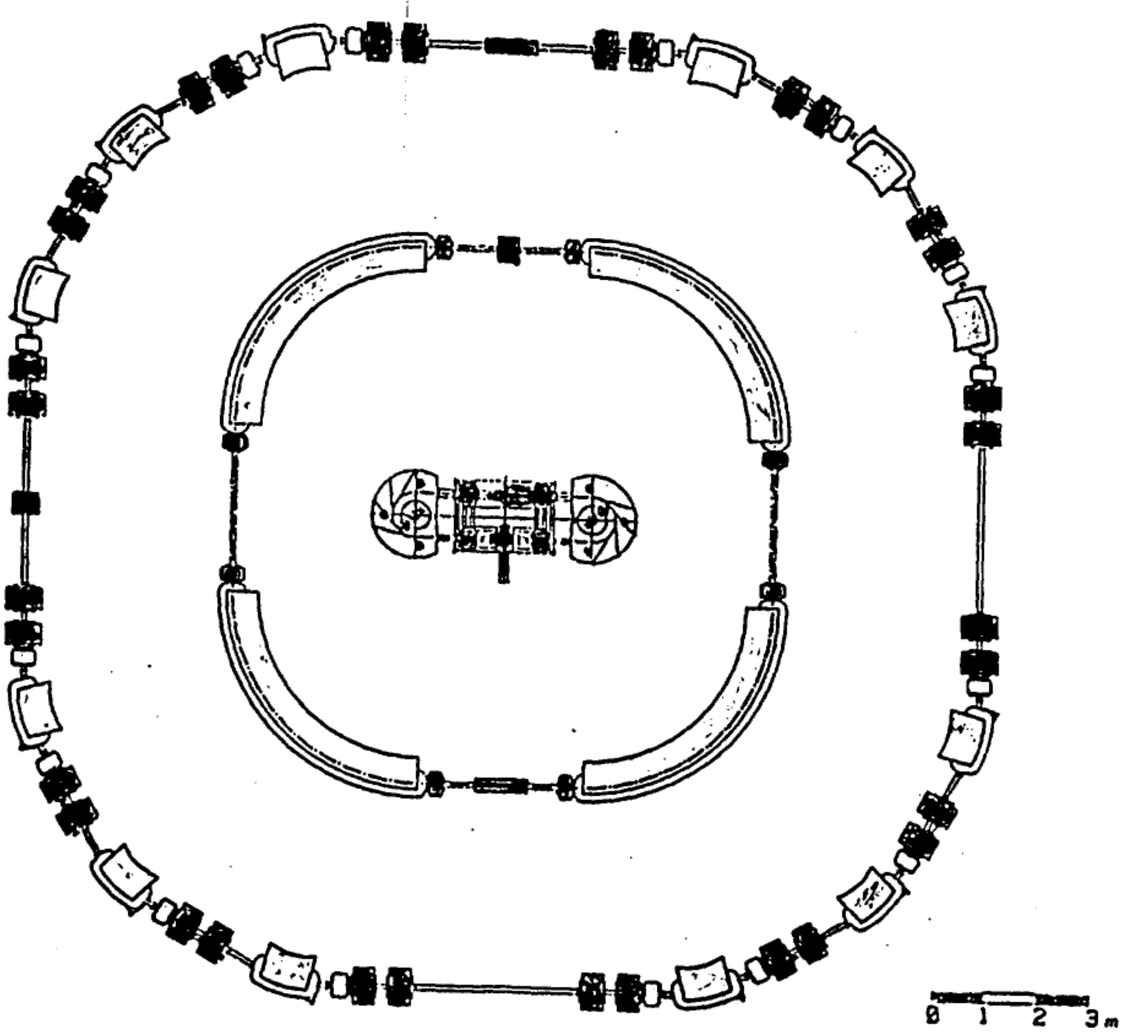


Fig. 1 Comparison between the BESSY storage ring, large Conventional ring with 1 T magnets and COSY

34498

Excised pig heart

subtracted image

iodine conc. 20 mg/l

E. B. Hughes et al.

1982

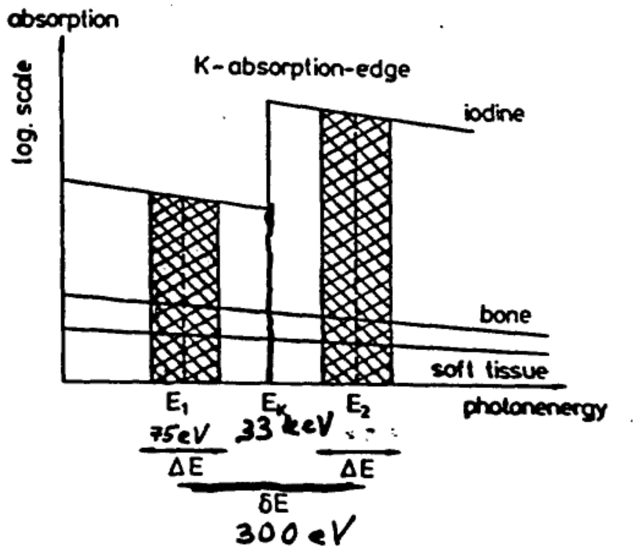


Figure 1.1: Energy dependence of absorption coefficients

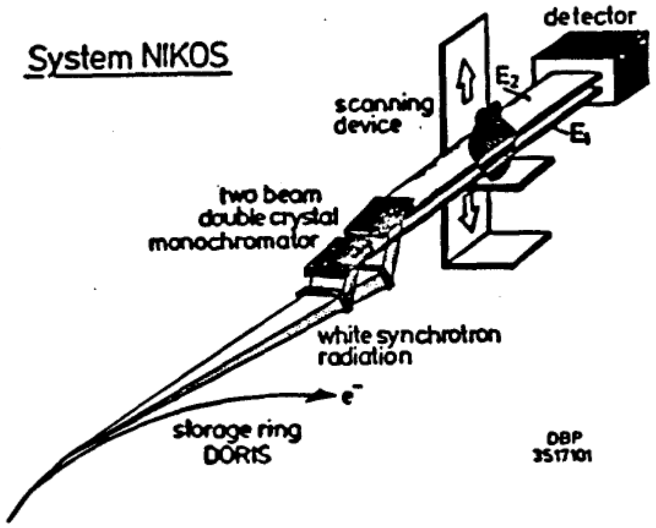


Figure 2.1: Experimental scheme.

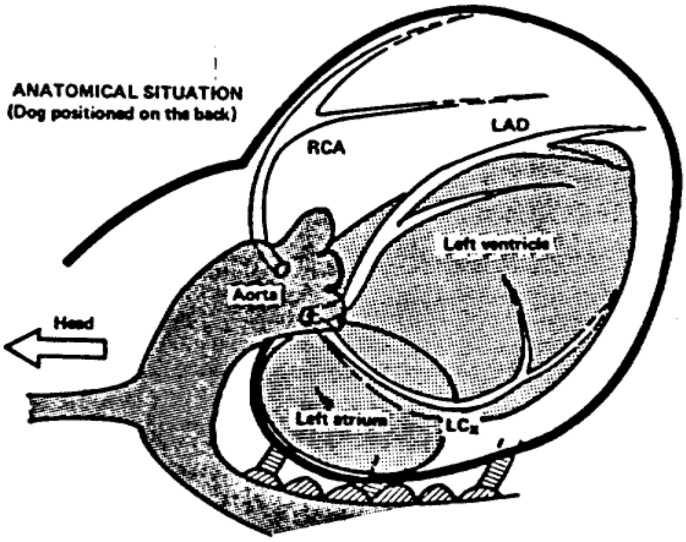


Fig. 3.1: Aorta of a dog (width of the scan: $45mm$). The contrast medium is applicated into the aorta. The white line gives the contour of the aorta in the part not opacified. The right coronary artery is visible below the aorta.
Fig. 3.2: Expected anatomical situation in the scan shown in Fig.3.3.

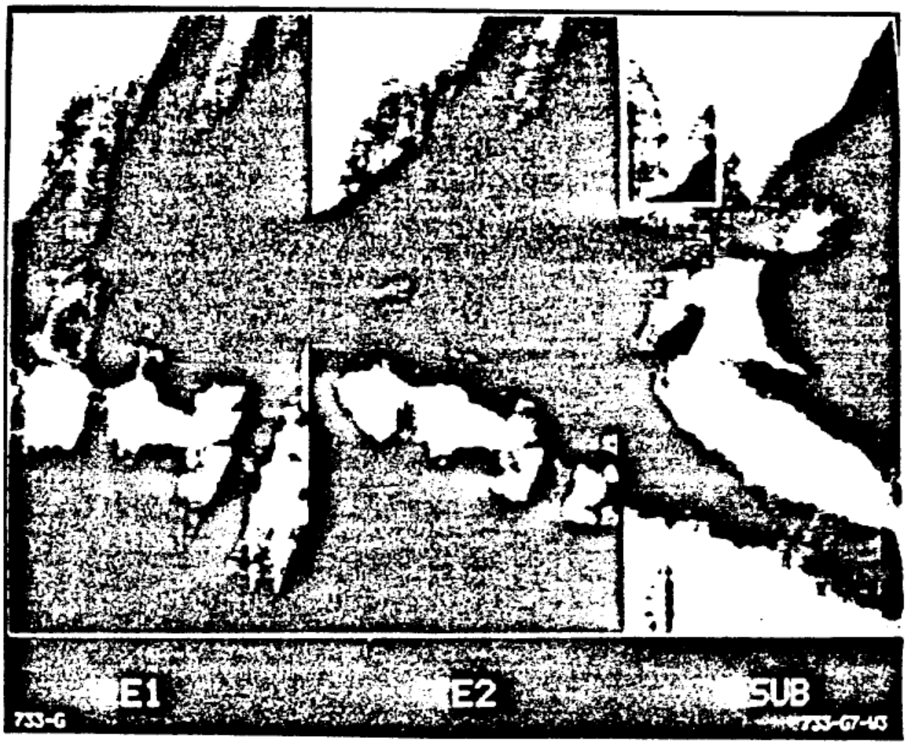
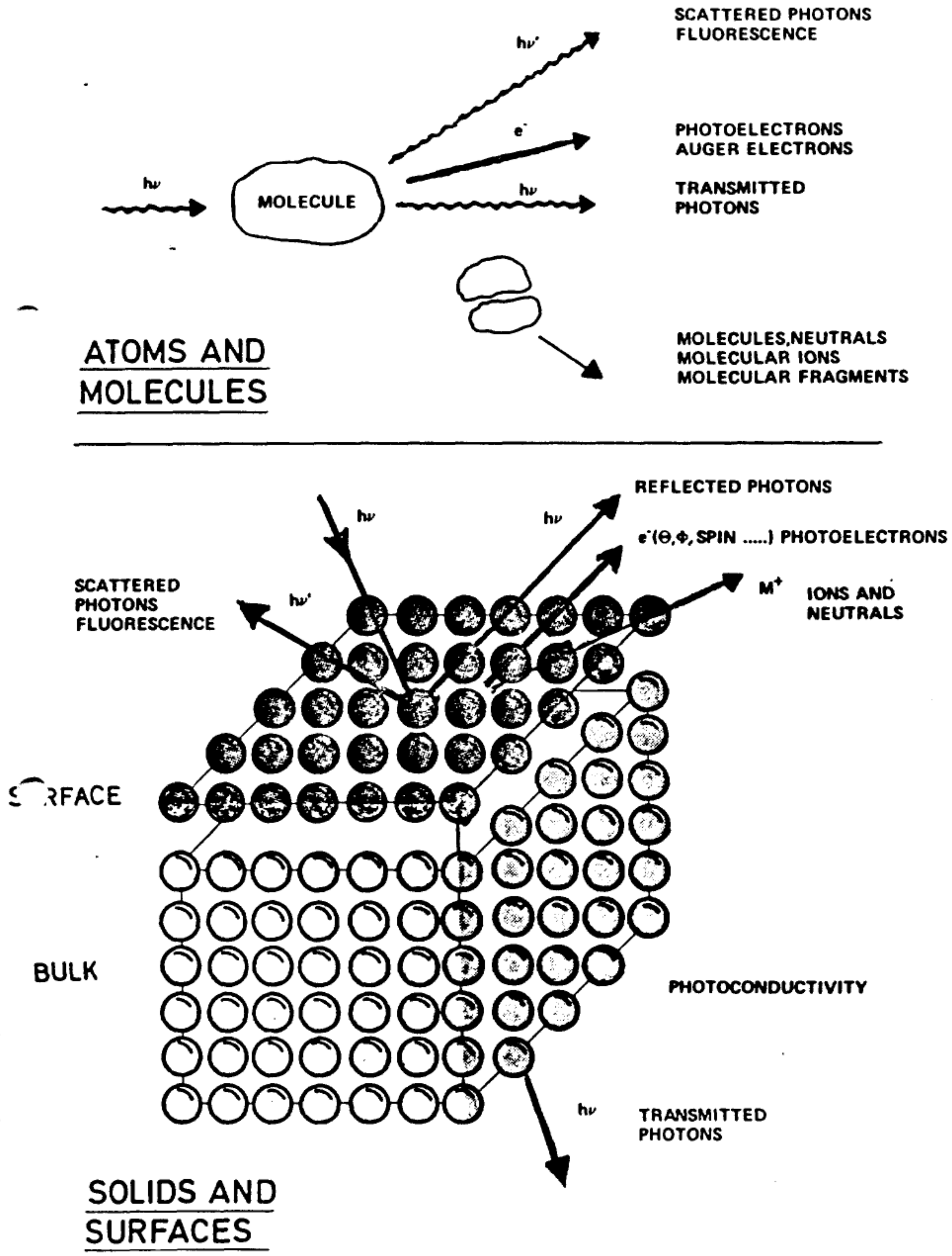


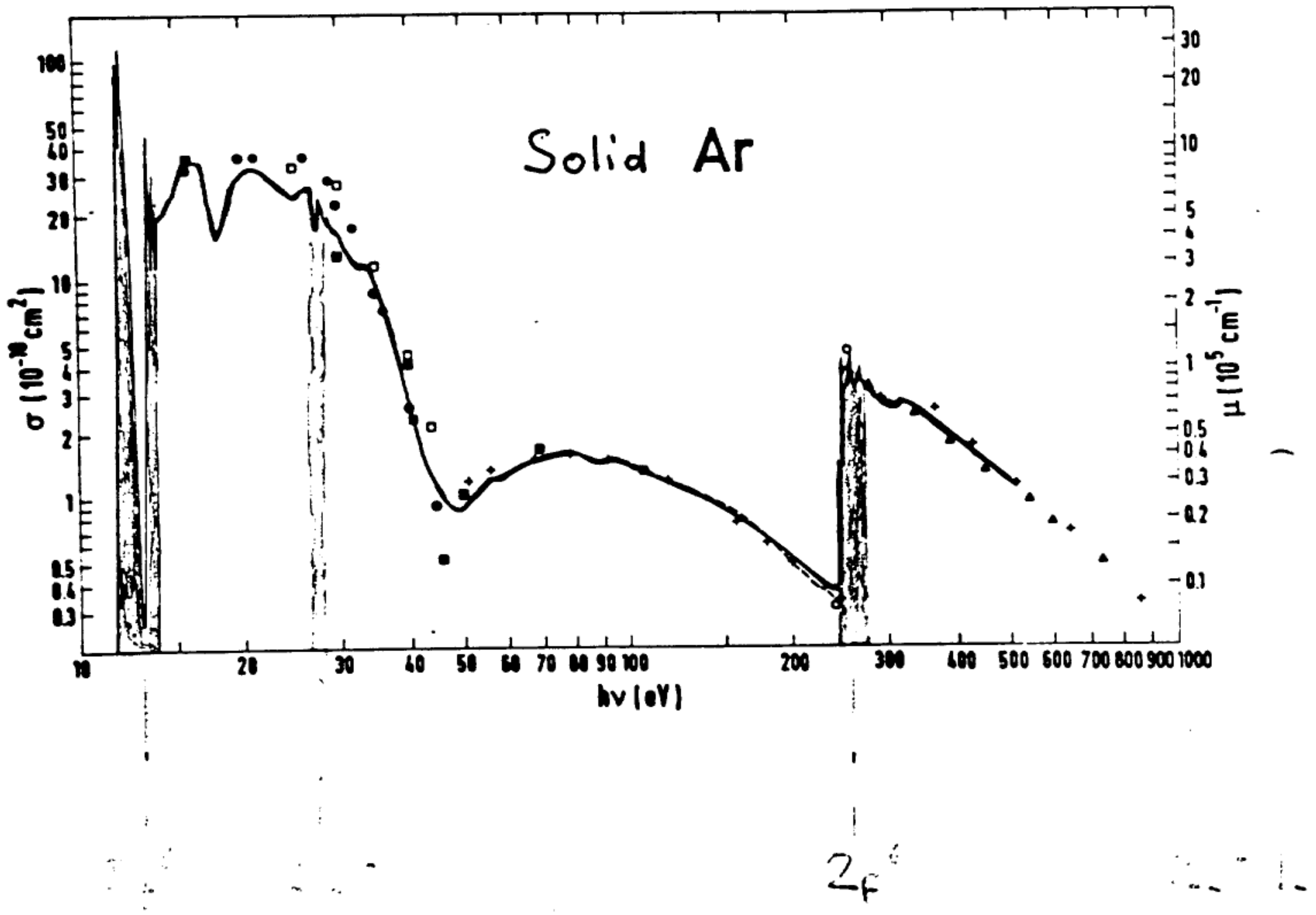
Fig. 3.3: Images with energy E_1 and E_2 and the corresponding subtraction image.

Figure 4.4: Left anterior descending coronary artery at the right side of the figure (arrow).

Figure 4.5: Visualization of the complete right coronary artery, parts of the left anterior descending coronary artery superposed by the left ventricle and the marginal branches of the circumflex coronary artery (arrow).

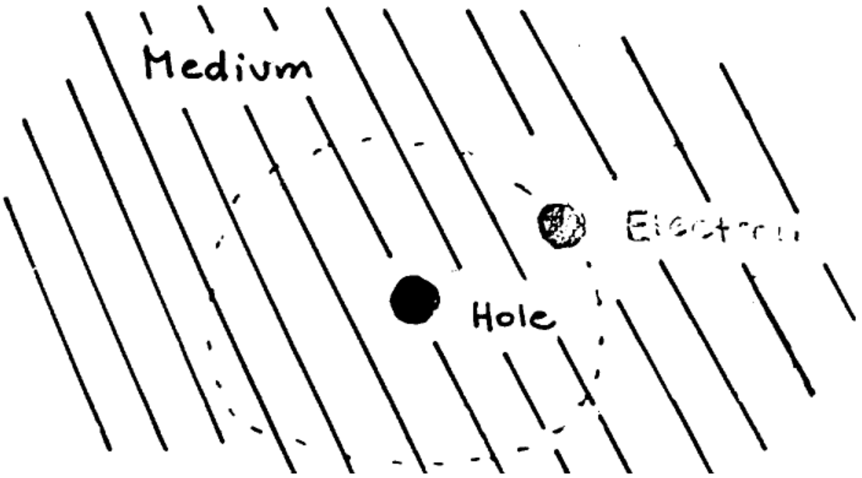


27. Upper panel: the interaction of photons with molecules is schematically depicted indicating many possible spectroscopies. Lower panel: photo-excitation spectroscopies applied to solids and aces. Atoms in the outermost surface layer have different geometries and physical properties than underlying bulk

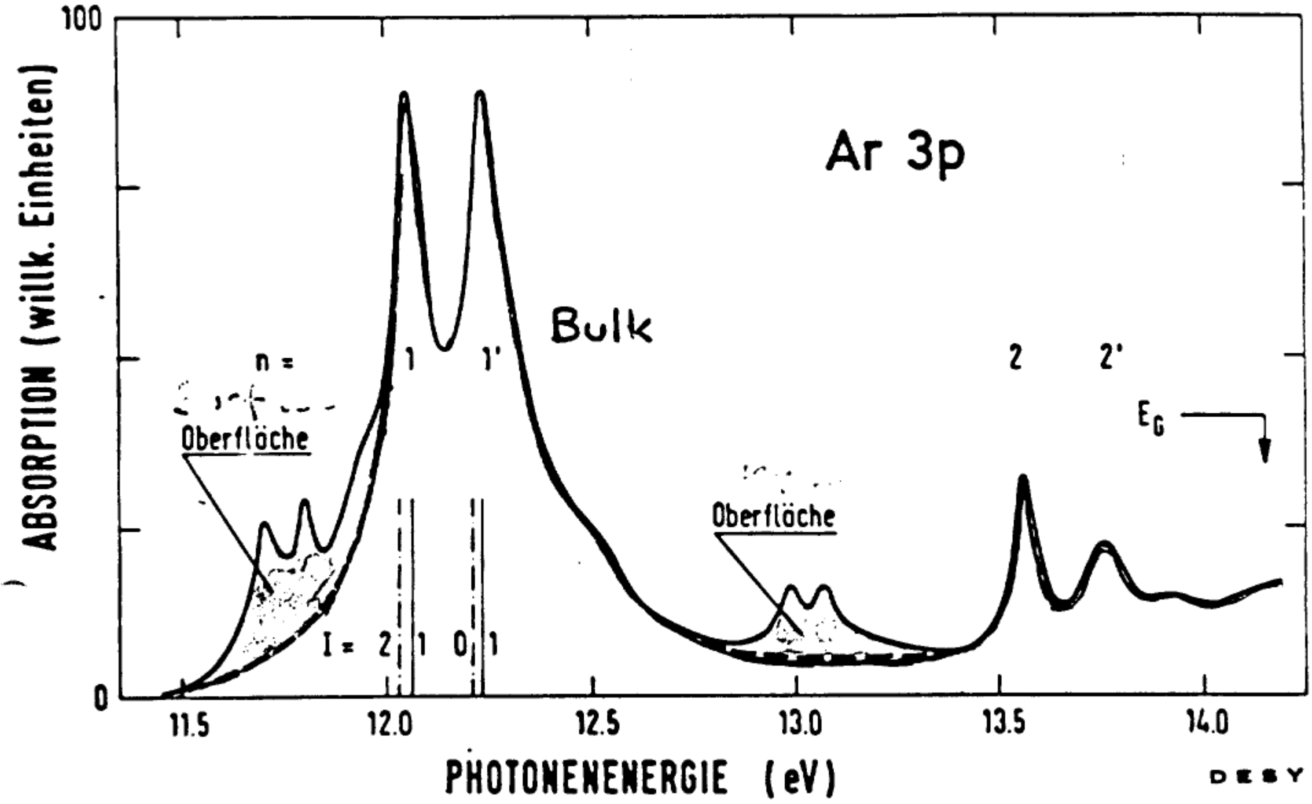


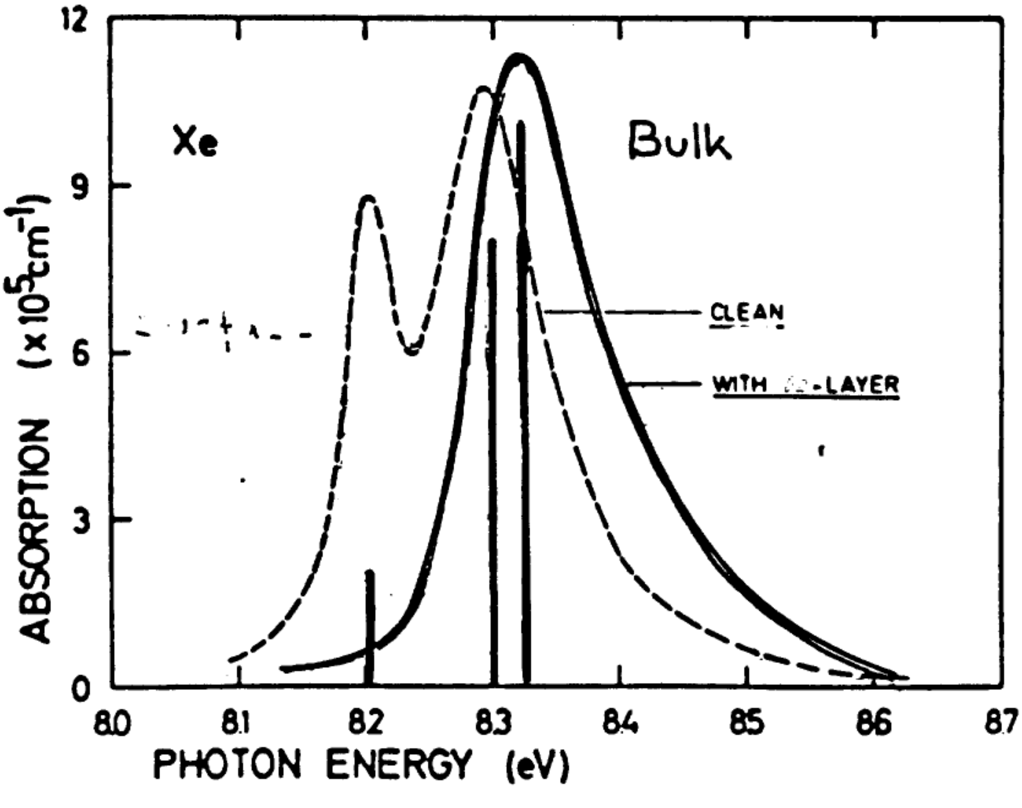
(Haensel, Keitel, Koch, Skibowski, Schreiber 1969)

Excitons :



Surface Excitons





(Saile, Skibowski, Steinmann, Gürtler
Koch, Kozeunikov 1976)

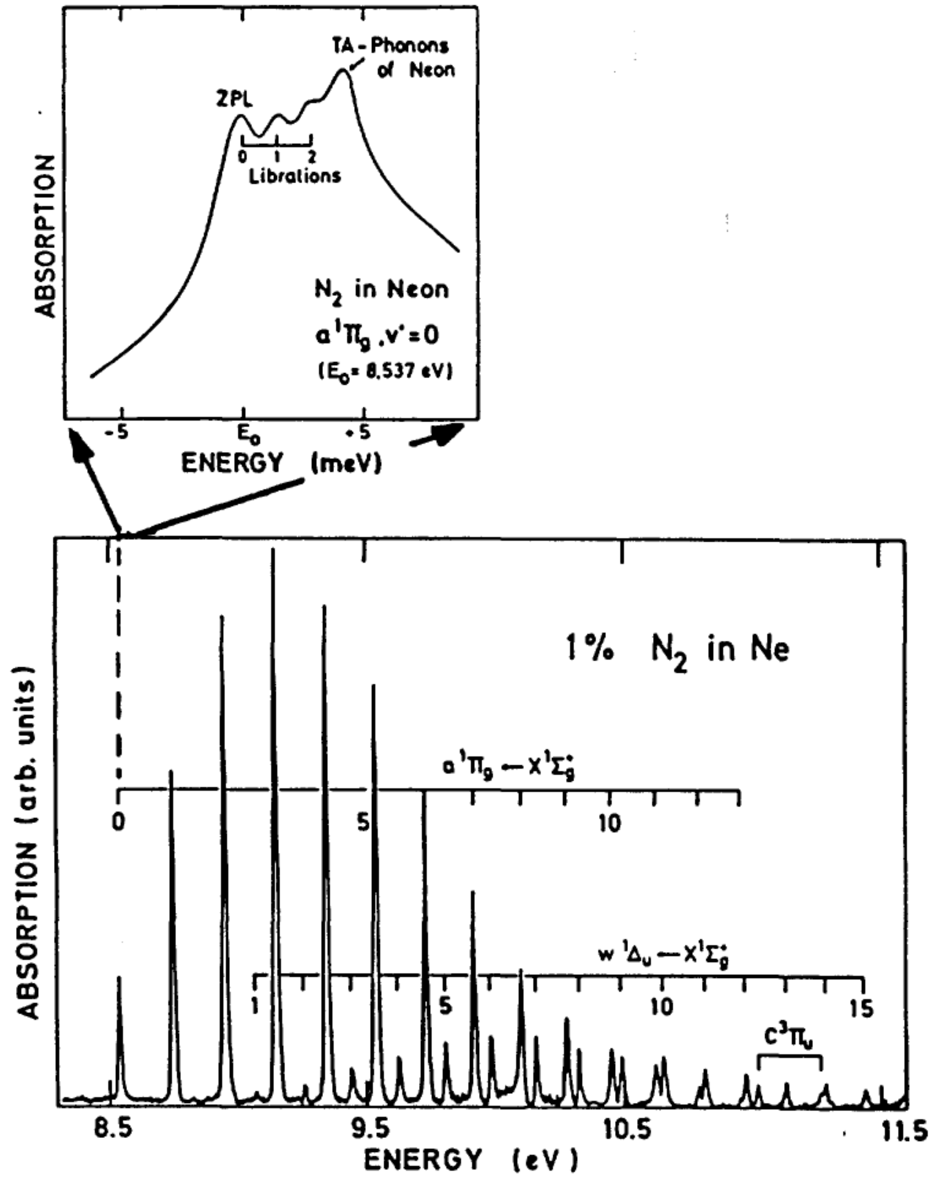


Abb. 2.7:

Absorptionsspektrum von Stickstoffmolekülen in einer Neon-Matrix. In dem Spektralbereich von 8.5 bis 11.5 eV werden drei in der Gasphase dipolverbotene elektronische Übergänge mit hoher Auflösung beobachtet. Jeder dieser Übergänge zeigt eine regelmäßige Schwingungsprogression. Für einen Übergang ist die Feinstruktur dargestellt, die Librationsschwingungen der N_2-Moleküle und die Anregung eines Phonons der Neon-Matrix zeigt /5/.

Niemann, Lübcke, Malzfeldt, Rabe, Haensel 1984

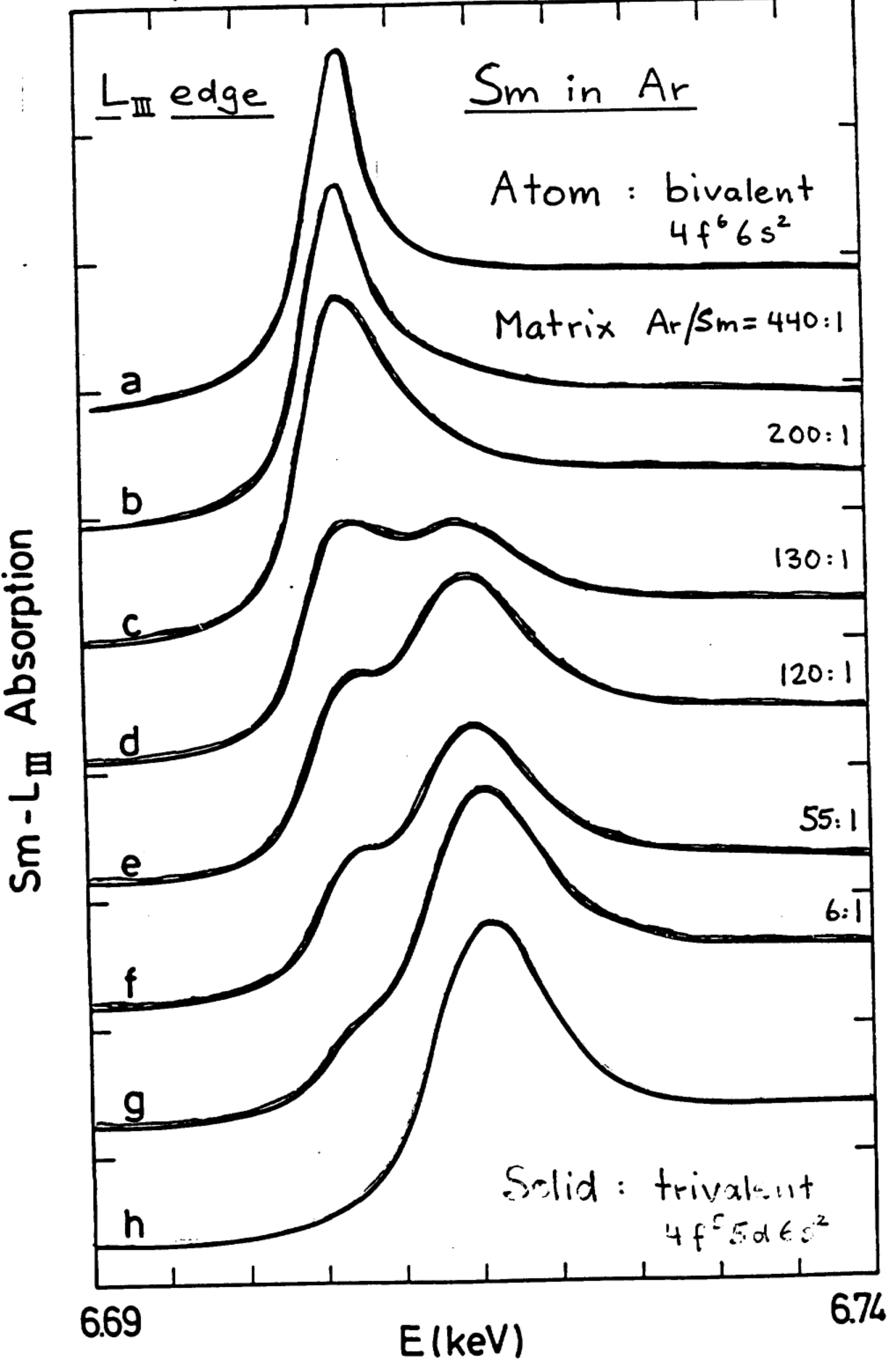


Fig. 1

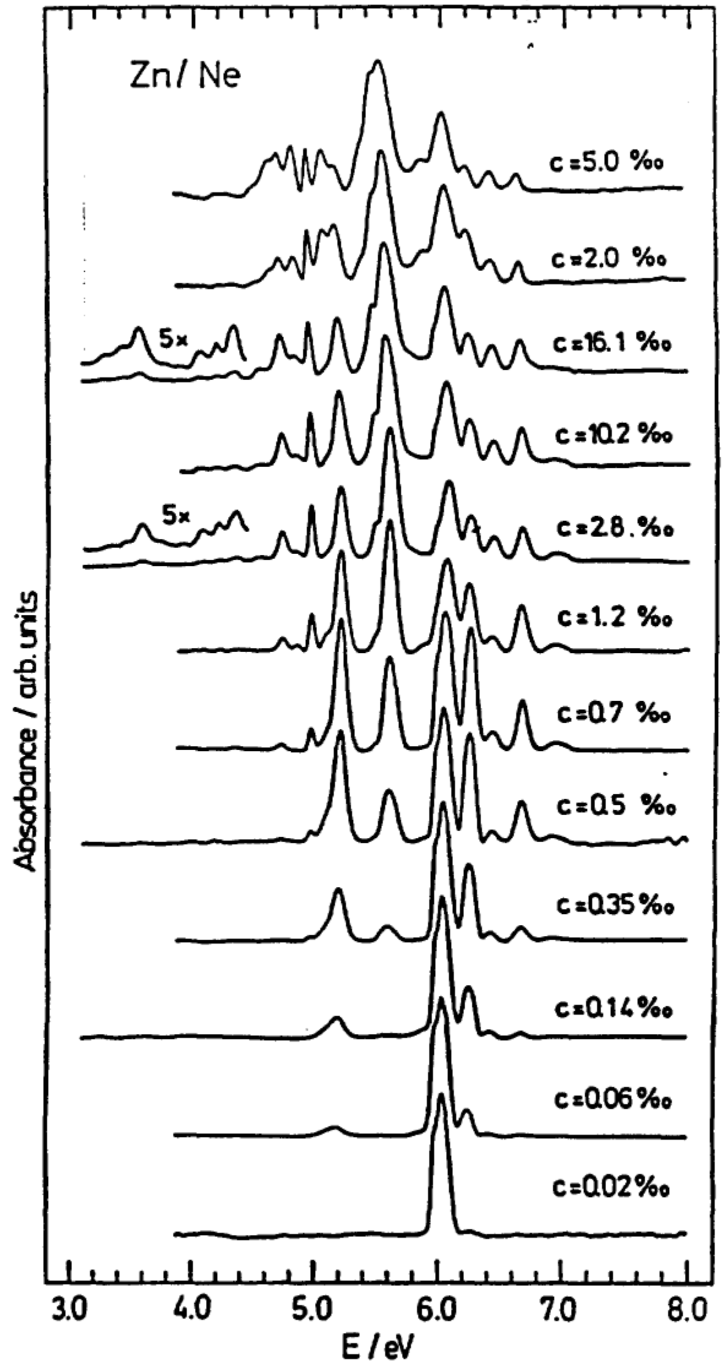
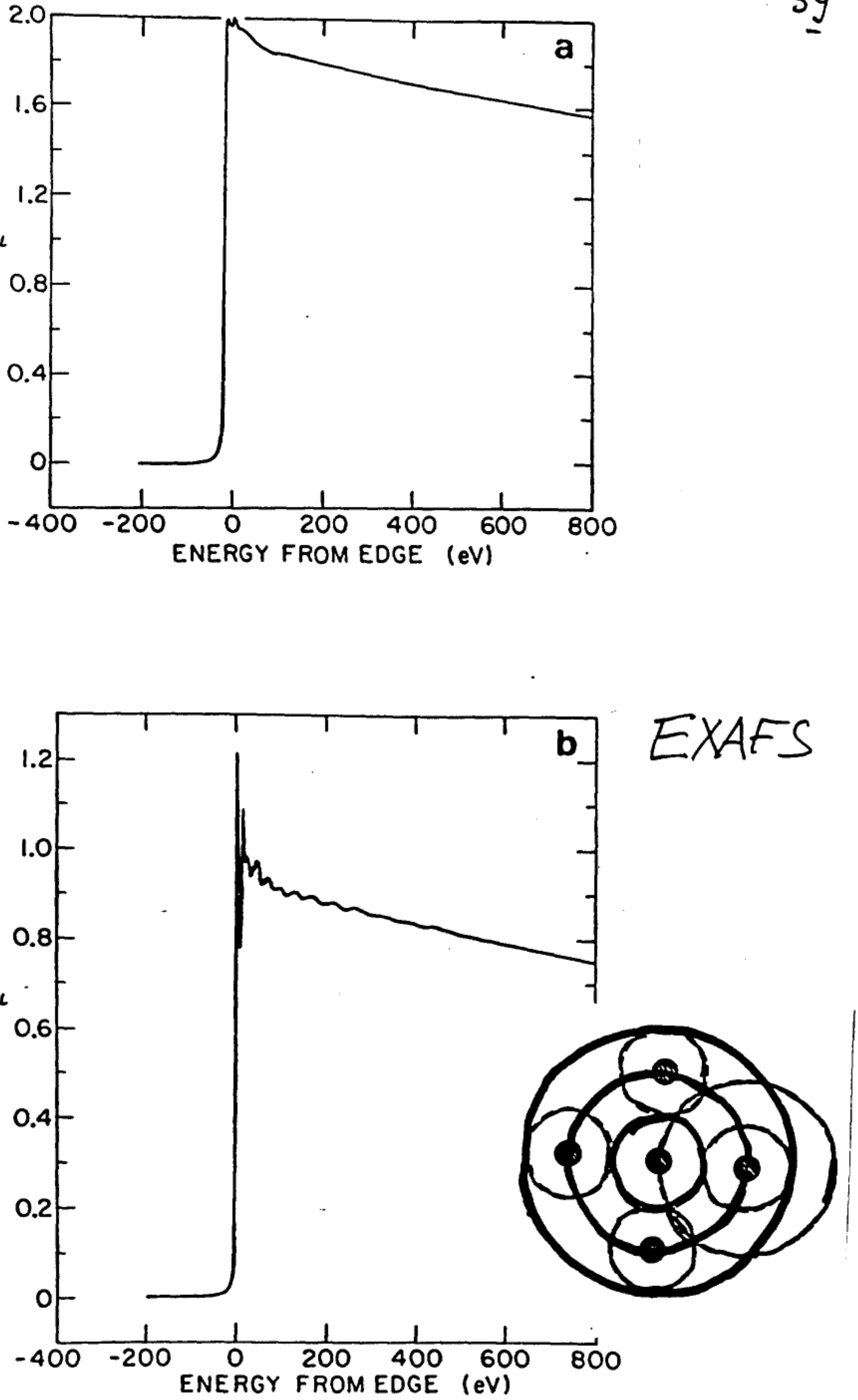


Abb. 1: Absorptionsspektren von Zn in Ne-Matrizen mit zunehmender Metallkonzentration. Das unterste Spektrum einer Matrix mit ausschließlich Zn-Atomen zeigt nur den ersten erlaubten Übergang $^1S_0 \rightarrow {}^1P_1$ des Zn-Atoms bei 6 eV. Die Zn-Konzentration nimmt in den Spektren darüber immer mehr zu, so daß die Absorptionsbanden zuerst von Zn_2, dann von Zn_3 und höheren Clustern zusätzlich entstehen.



EXAFS

Fig. 2. (a) The X-ray absorption coefficient, μ, times thickness, x, of isolated krypton atoms in the vapor form. The small structure near the edge is due to transitions to bound states. (b) The X-ray absorption coefficient times thickness of about one monolayer of krypton adsorbed on Grafoil, a form of graphite. The added structure is produced by the atomic neighbors.

2. Example: Extended x ray absorption fine structure

SEXAFS

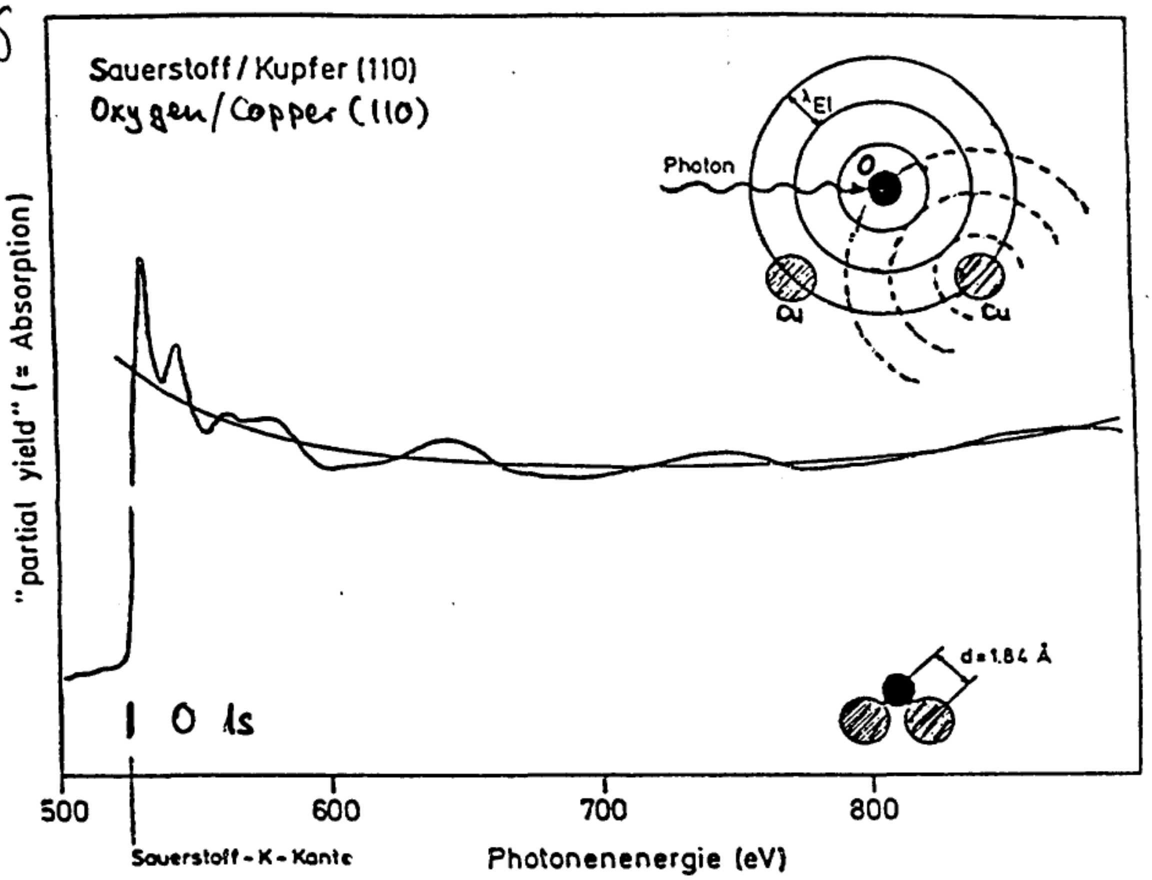
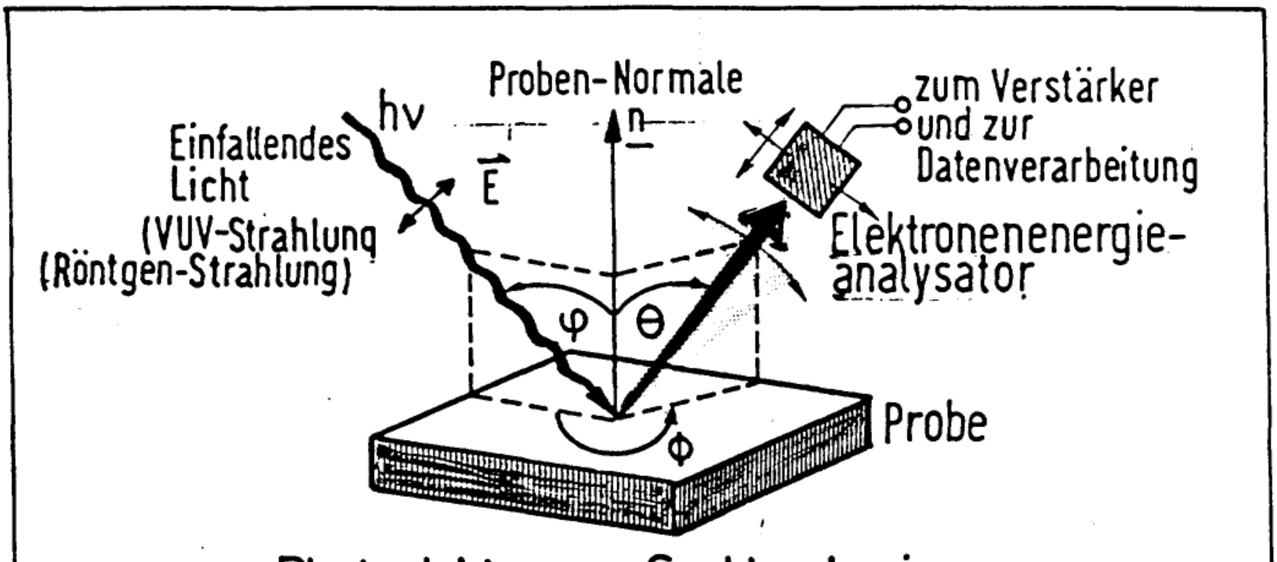


Abb. 2: EXAFS an der Sauerstoff-K-Kante für eine mit Sauerstoff belegte Kupfer(110)-Oberfläche. Die Sauerstoffatome bilden eine geordnete Überstruktur (als 2 x 1 bezeichnet), die durch Beugung niederenergetischer Elektronen (LEED) nachgewiesen wurde. Die Bedeckung entspricht einer halben Monolage. Als Adsorptionsplatz wurde die sog. lange Brücke mit einem Sauerstoff-Kupfer-Abstand von 1,34 Å ermittelt. Aus Untersuchungen bei BESSY von Döbler <u>et al</u>. (Phys. Rev. Lett. <u>52</u> (1984) 1437) sowie Puschmann <u>et al</u>. (unveröffentlicht). Oben rechts ist schematisch die physikalische Grundlage von EXAFS dargestellt.

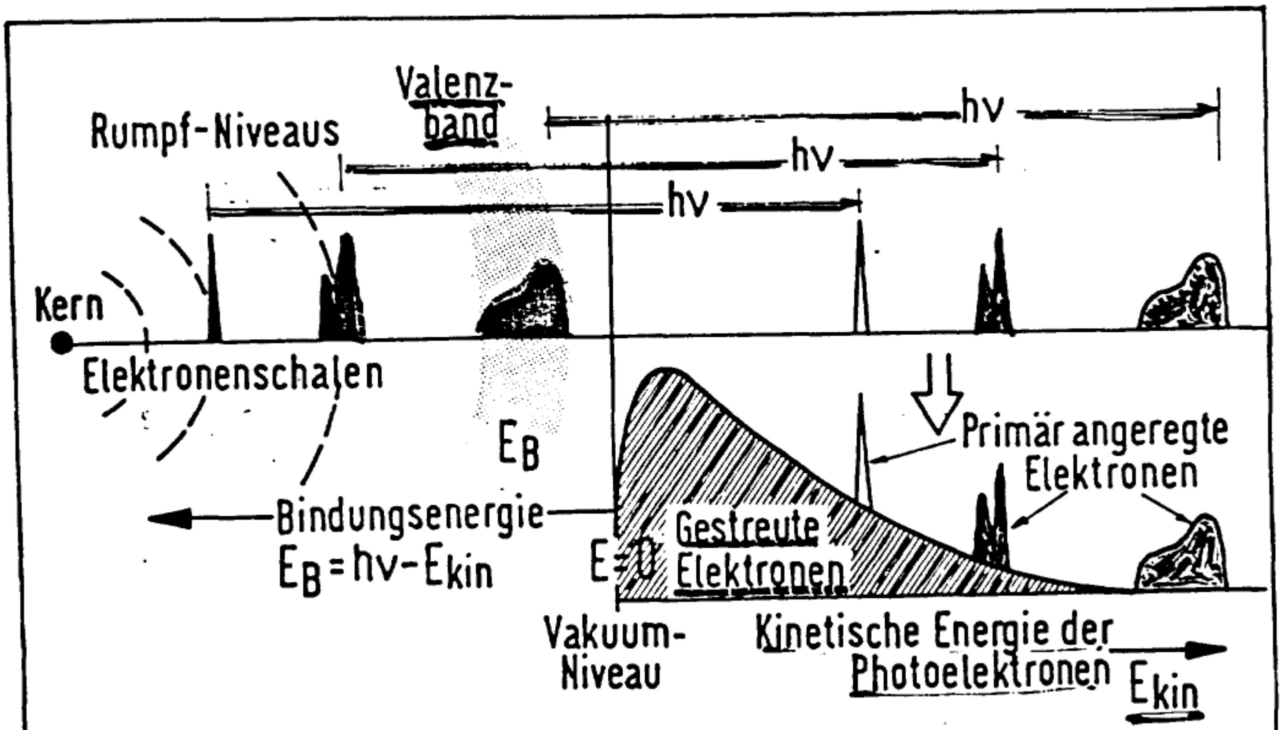
Large tuneability required

initial phase ?

scattering phase ?



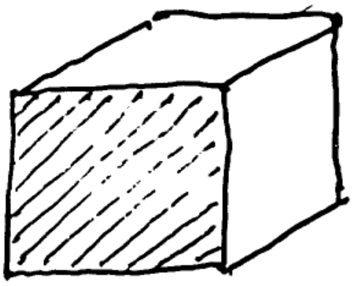
Photoelektronen-Spektroskopie



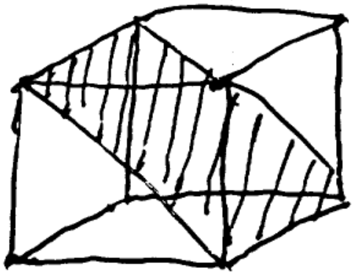
Messung

35429

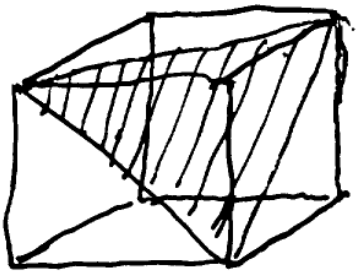
100



110



111



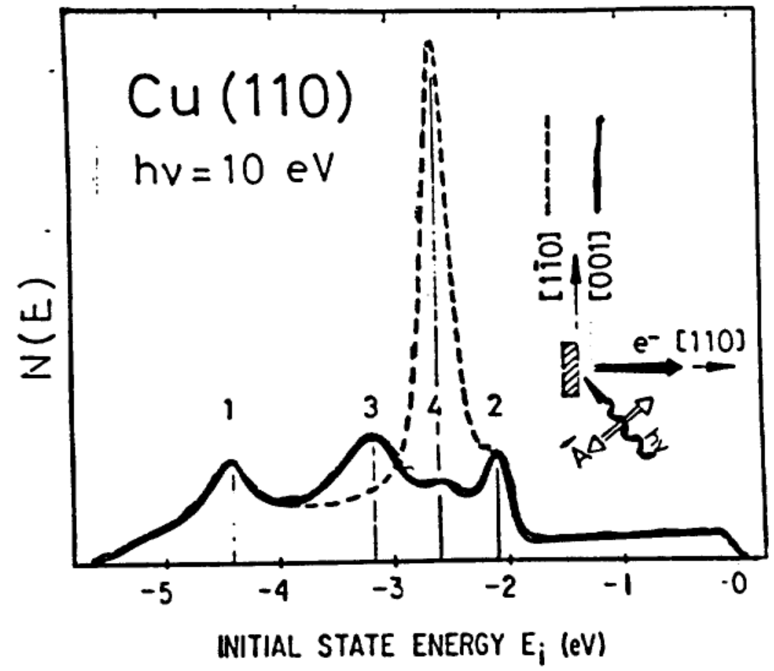


Fig. 14. Photoelectron energy spectra for normal emission from Cu(110) using p-polarized light. Th full (dashed) curves correspond to alignment of the component of the *A* vector parallel to the surfac along [001] (or [1$\bar{1}$0]) respectively and demonstrate the operation of the dipole symmetry selection rul (Dietz and Himpsel 1979).

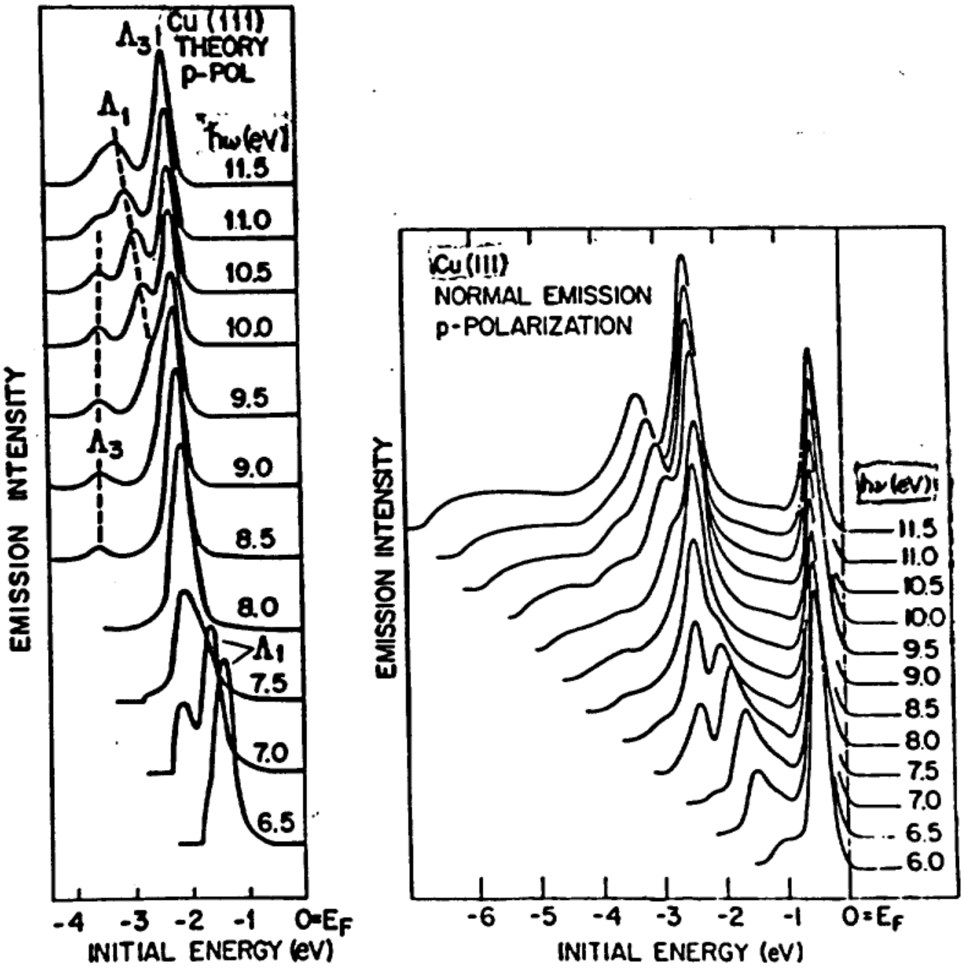


Fig. 15. Theoretical spectra (on the left) are compared with experimental spectra (on the right) for normal photoemission from Cu(111) for a range of photon energies using p-polarized light (from Smith et al. 1980b).

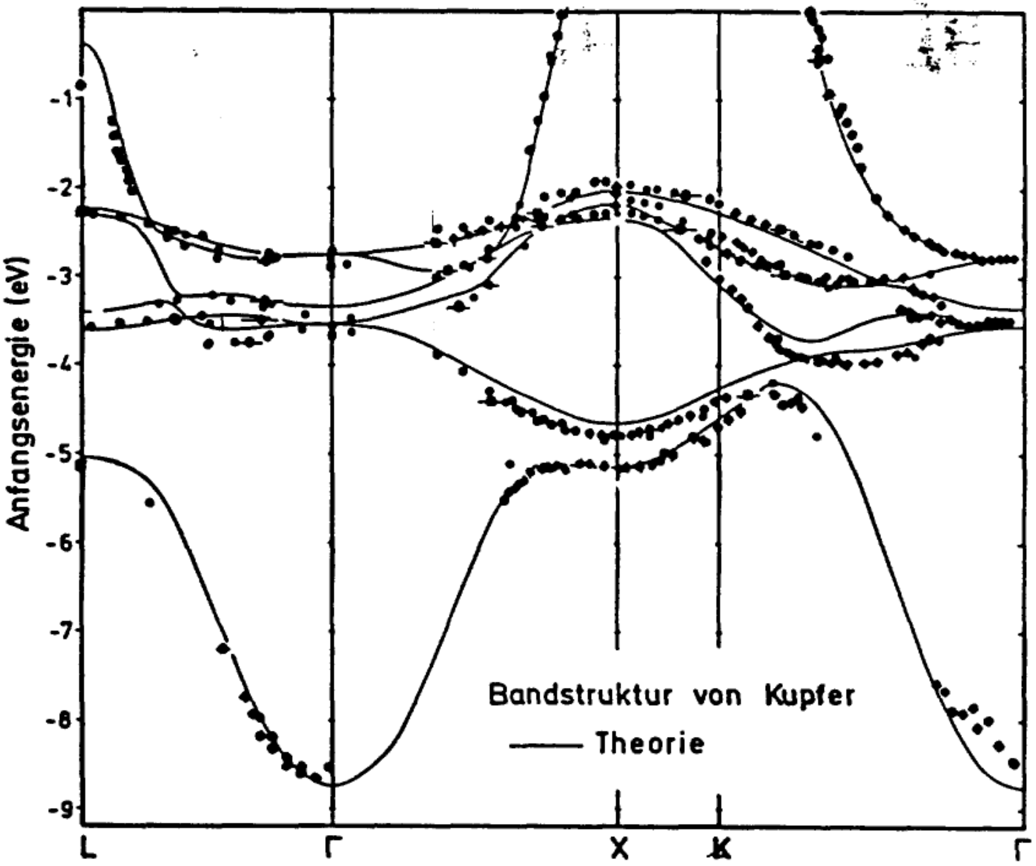


Abb. 2.8:

Ein Vergleich der experimentellen und theoretischen Bandstruktur von Kupfer. Die Kurven stellen die mittels der lokalen Dichtenäherung berechneten Bänder dar. Die Meßpunkte kommen von winkelaufgelösten Photoemissionsdaten verschiedener Autoren. Diese sogenannten "band-mapping" Experimente werden in der Regel mit der Triangulationsmethode durchgeführt: Der gleiche Übergang zwischen einem besetzten und einem unbesetzten Band wird bei der winkelaufgelösten Photoemission an zwei verschiedenen kristallographischen Flächen beobachtet, um den Ort des Übergangs in der Brillouinzone ($\underline{k}$-Wert) zu ermitteln. Da die Anfangsenergie aus dem Spektrum bekannt ist, kann damit die Dispersionsrelation $E(\underline{k})$ bestimmt werden. Nach Courths und Hüfner /2/.

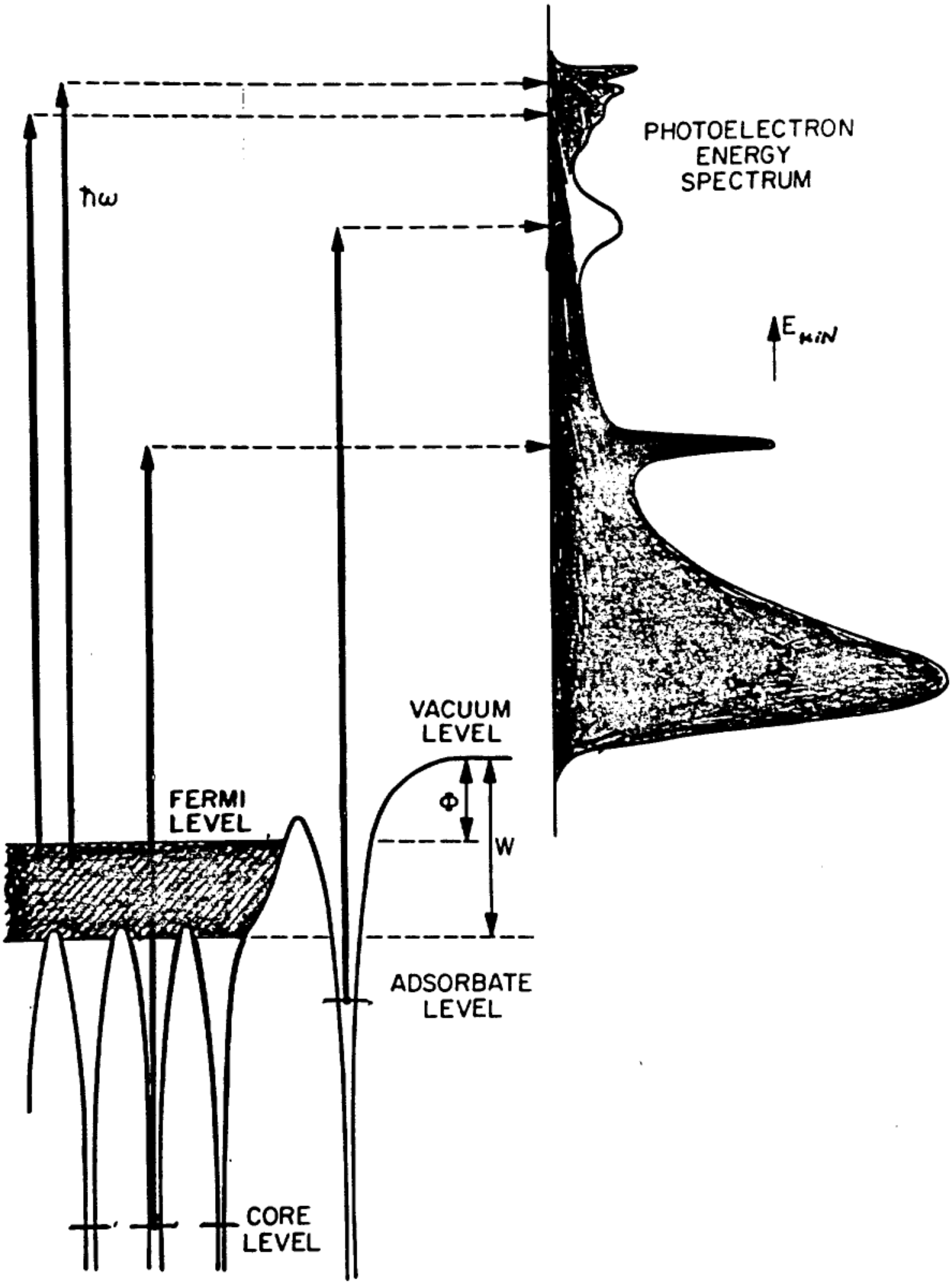


Fig. 1. Energetics of photoemission from a metallic solid, showing schematically the electroni potential, core levels, an adsorbate level, valence band (cross-hatched) and typical photoelectro energy spectrum at photon energy $\hbar\omega$. The work function Φ and the inner potential W are indicate

3 examples of surface investigations with synchrotron radiation

1.	Cl / GaAs (110)	surface corelevel shift angle integrating mode
2.	S / Ge (100)	
3.	CO / Pt (110)	: angular distribution of valence photoelectrons angle resolved mode

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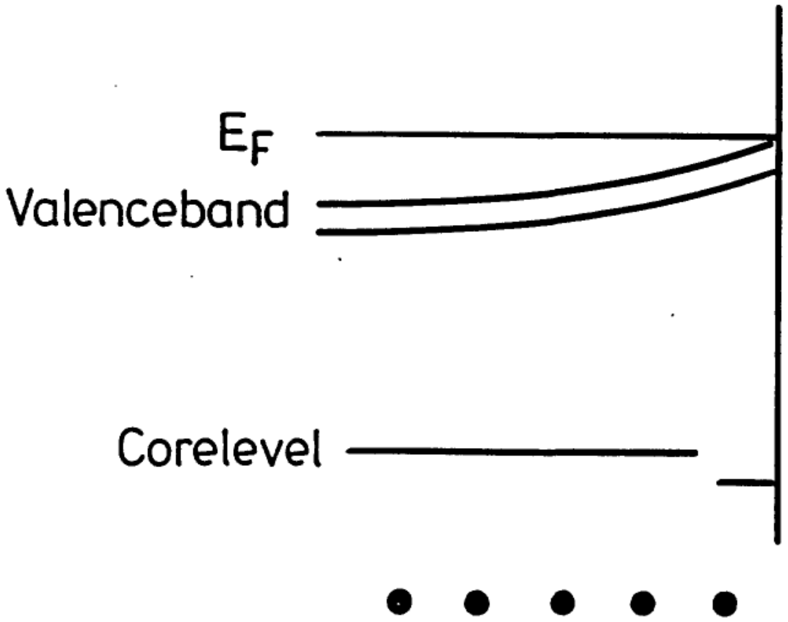
Surface Corelevel Shift



Variation of Surface Sensitivity with Photon Energy

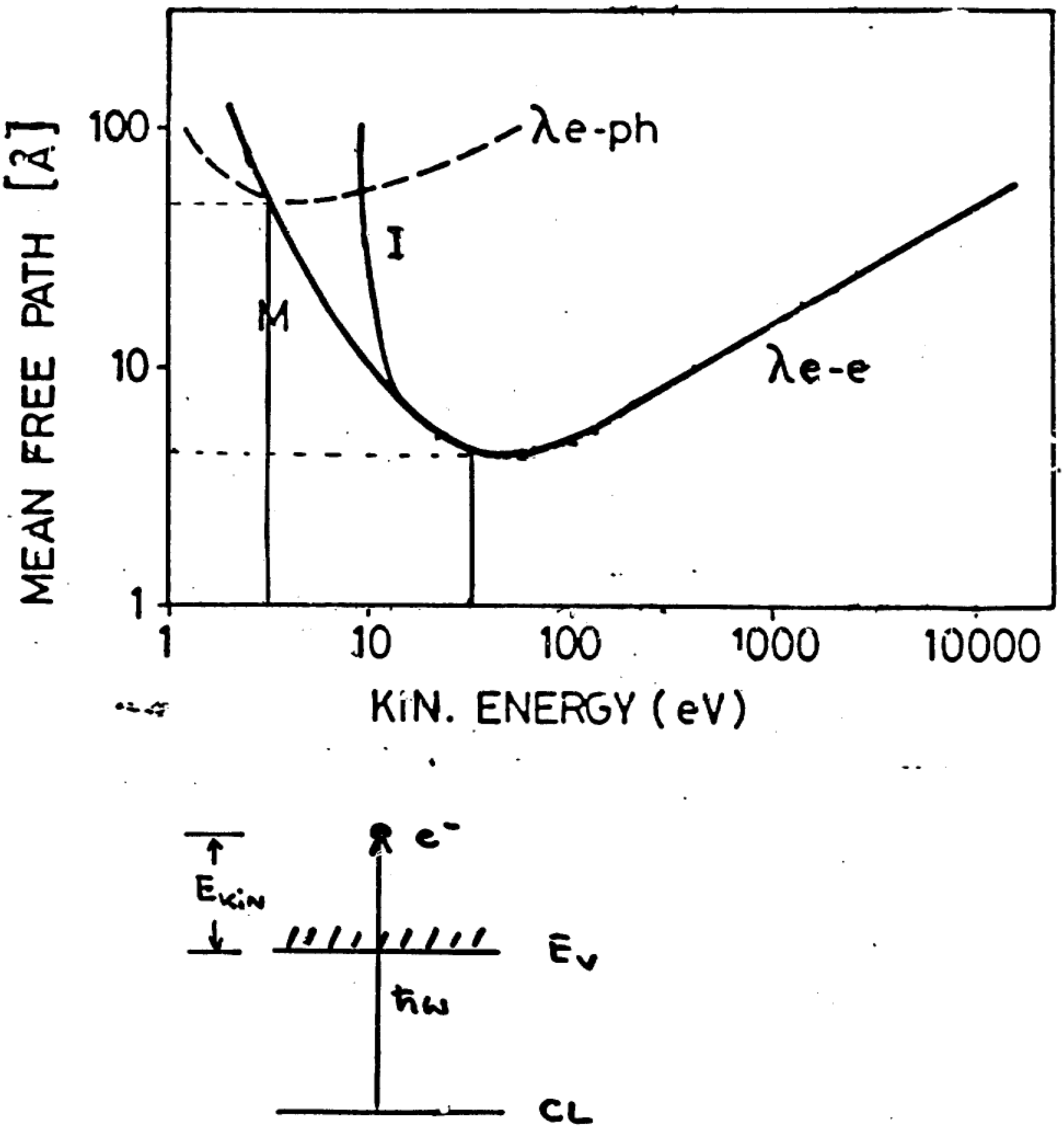
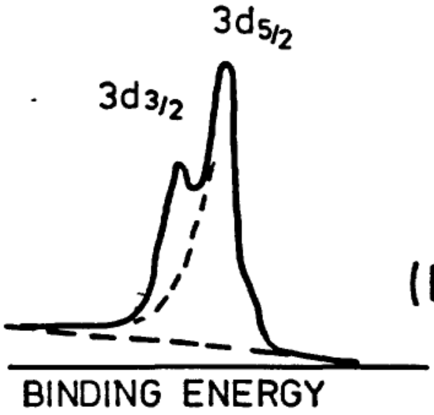
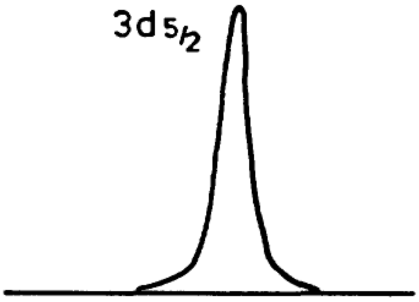


Figure 3

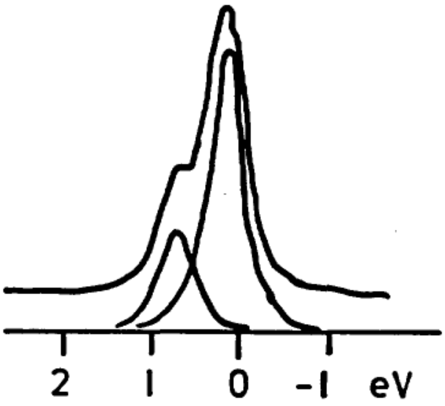
Corelevel Lineshape Analysis

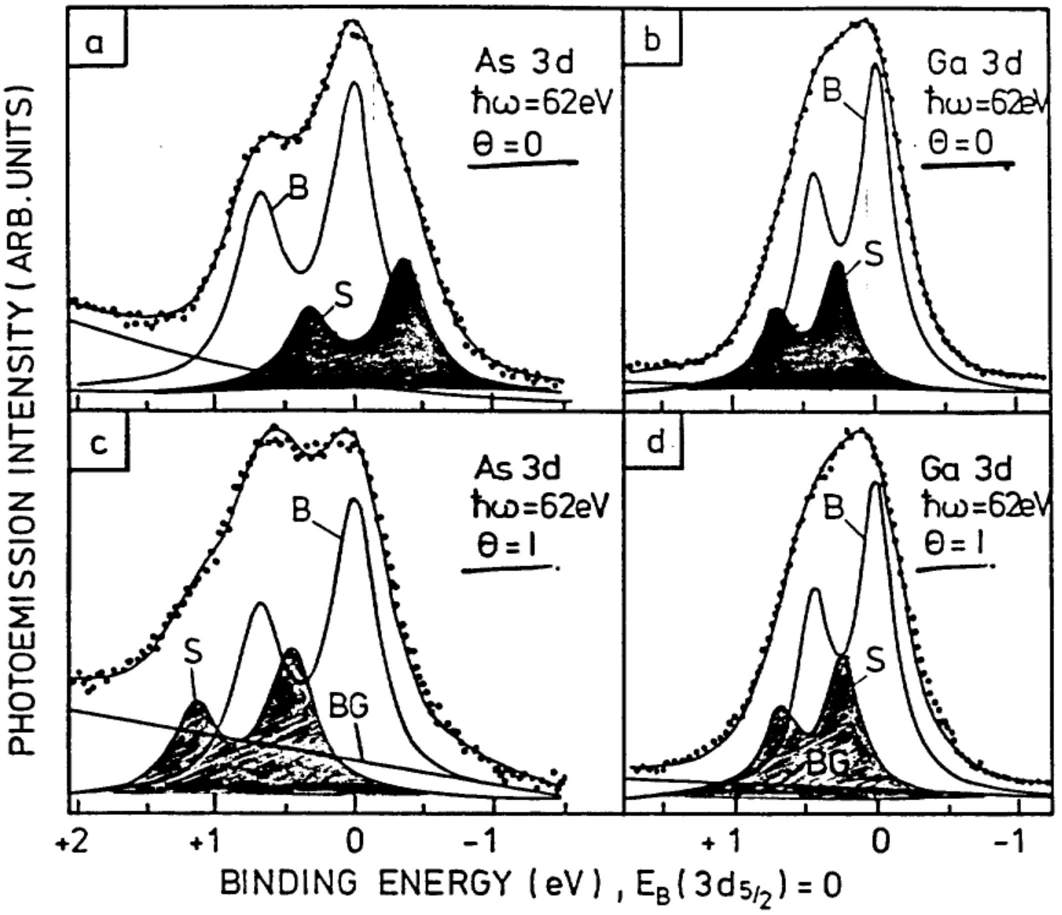


bulk
(E_{Kin}=5eV)

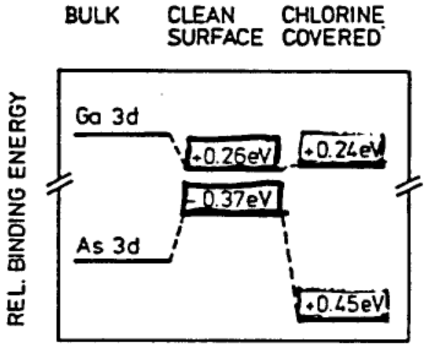


bulk
+
surface
(E_{Kin}=30eV)





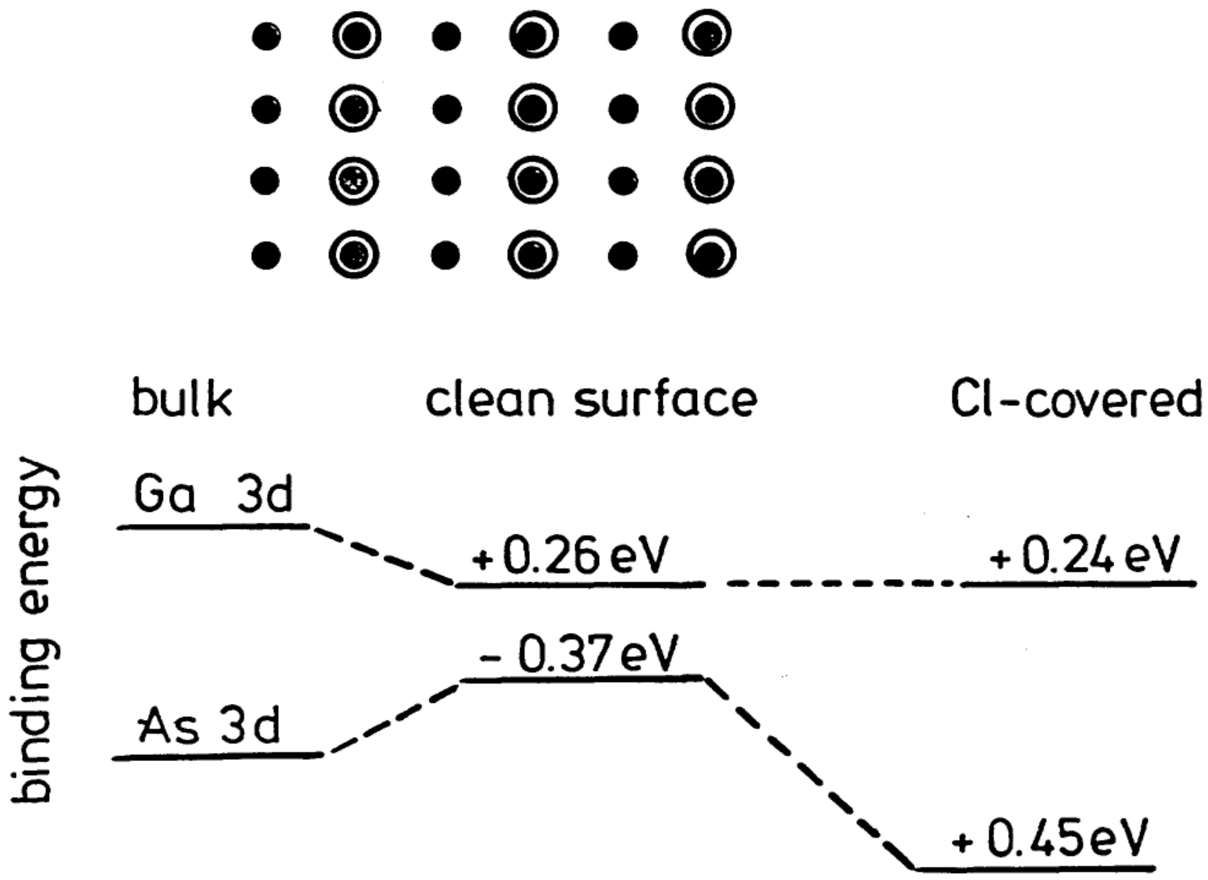
clean surface



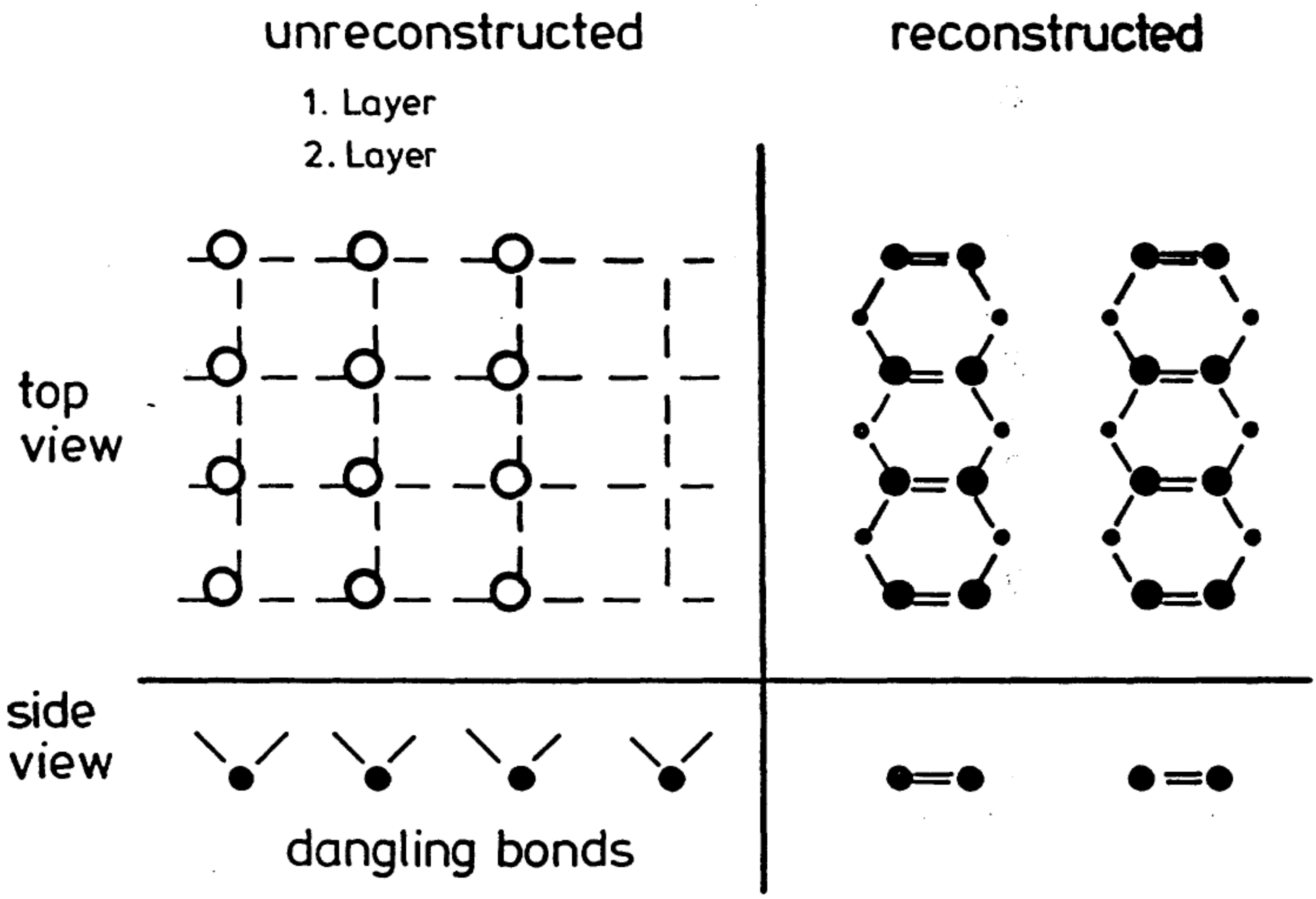
— starke Verschiebung des OF-Rumpfniveaus am As (+820 meV)

— geringfügige Verschiebung des OF-Rumpfniveaus am Ga (−20 meV)

Cl/ GaAs (110)


bulk
clean surface
Cl-covered
binding energy
Ga 3d
+0.26 eV
+0.24 eV
- 0.37 eV
As 3d
+ 0.45 eV

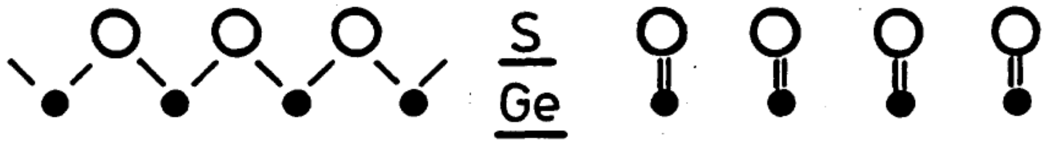
Ge (100)



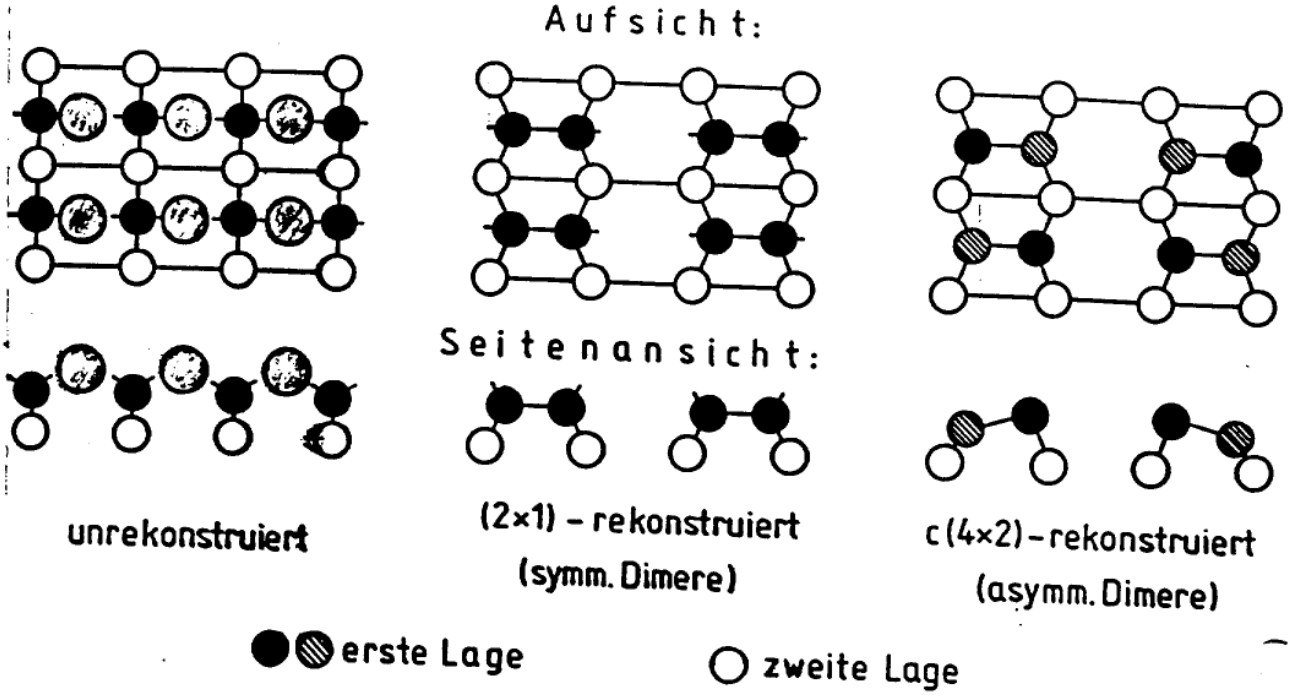
S-adsorption (1 monolayer) removes the reconstruction

site of S-Atom :

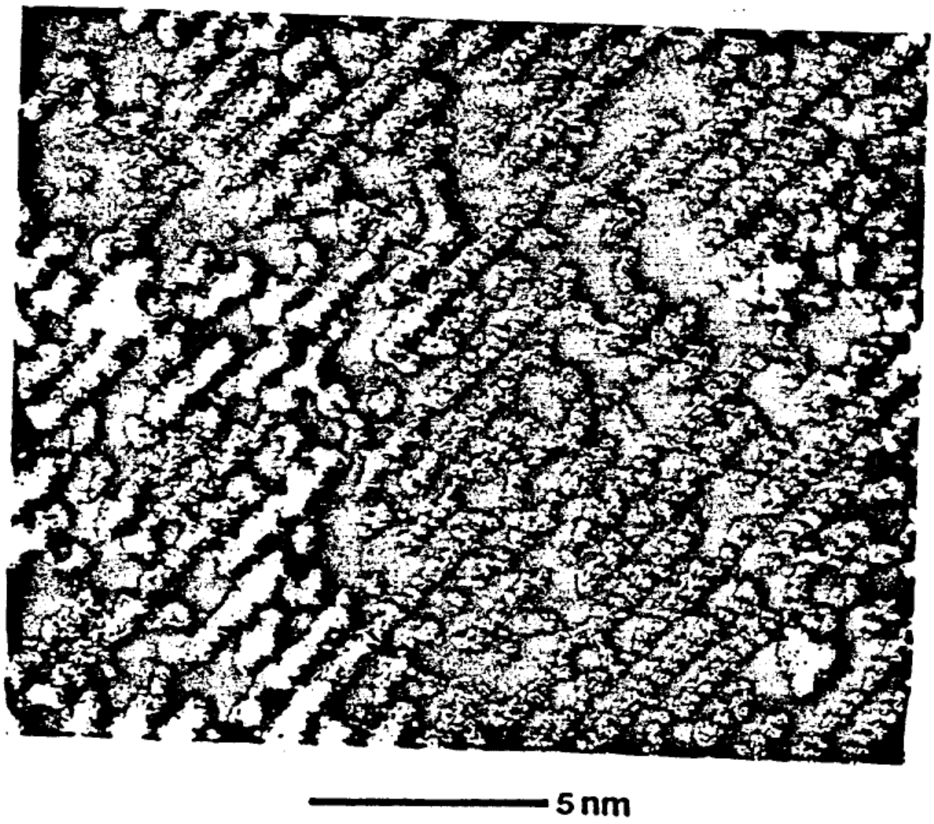
bridge or top ?



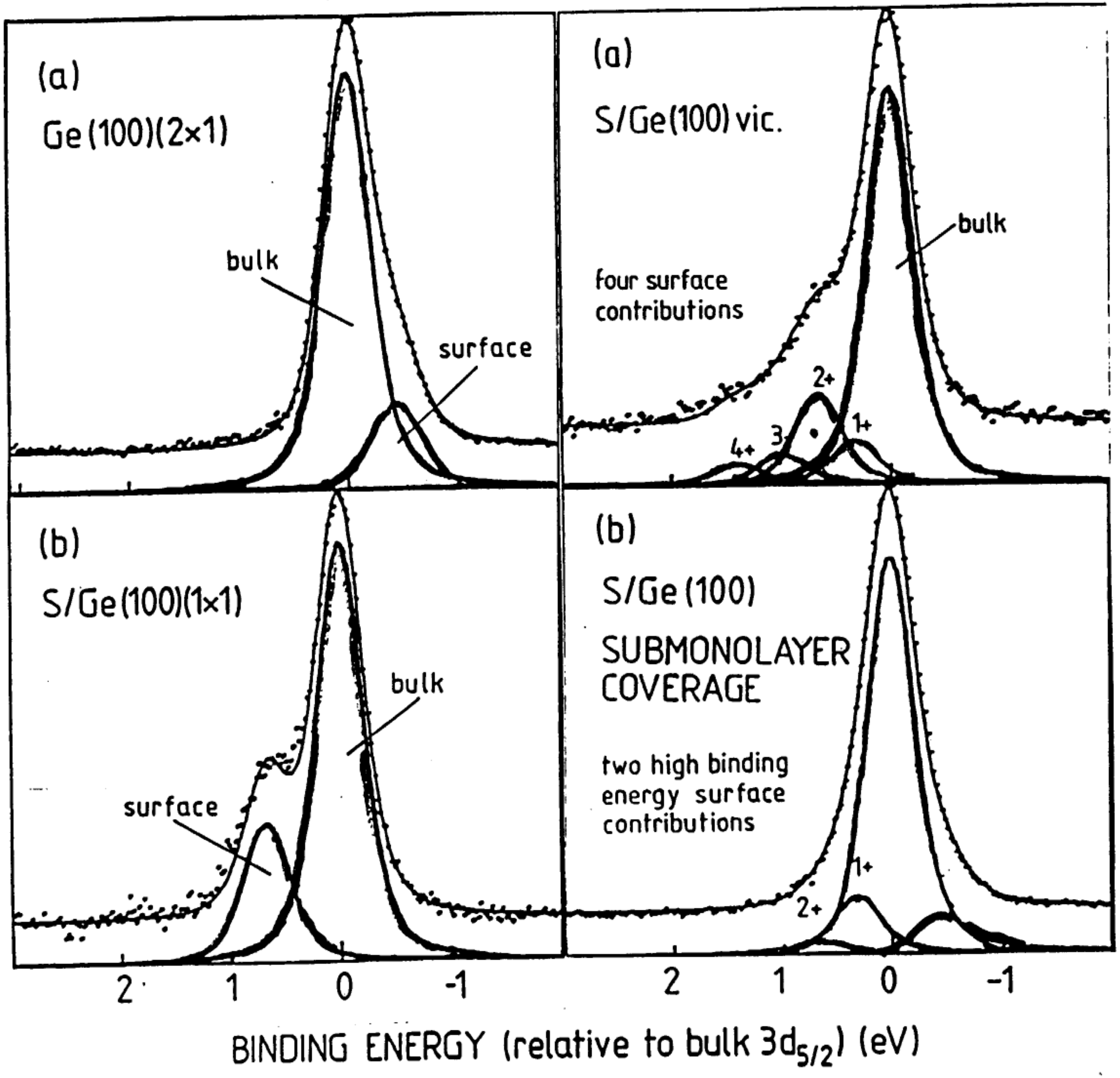
Si,Ge (100)- OBERFLÄCHE



Si (100) (2×1)



Ge $3d_{5/2}$ CORE-LEVEL PHOTOEMISSION



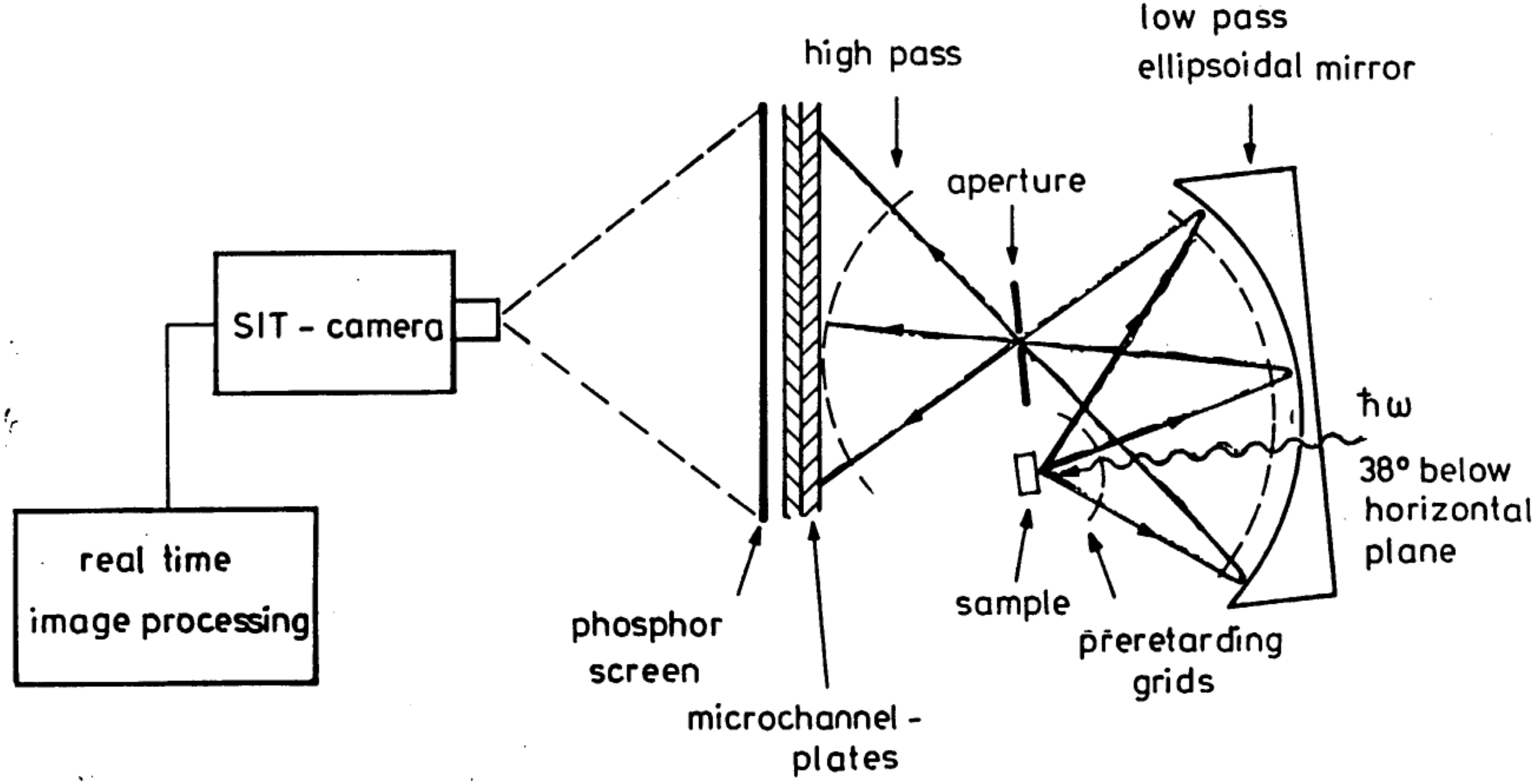
Eastman
Donelon
Hien
Himpsel
(Wisconsin)

IBM

Rieger
Schnell.
Steinmann
(BESSY)

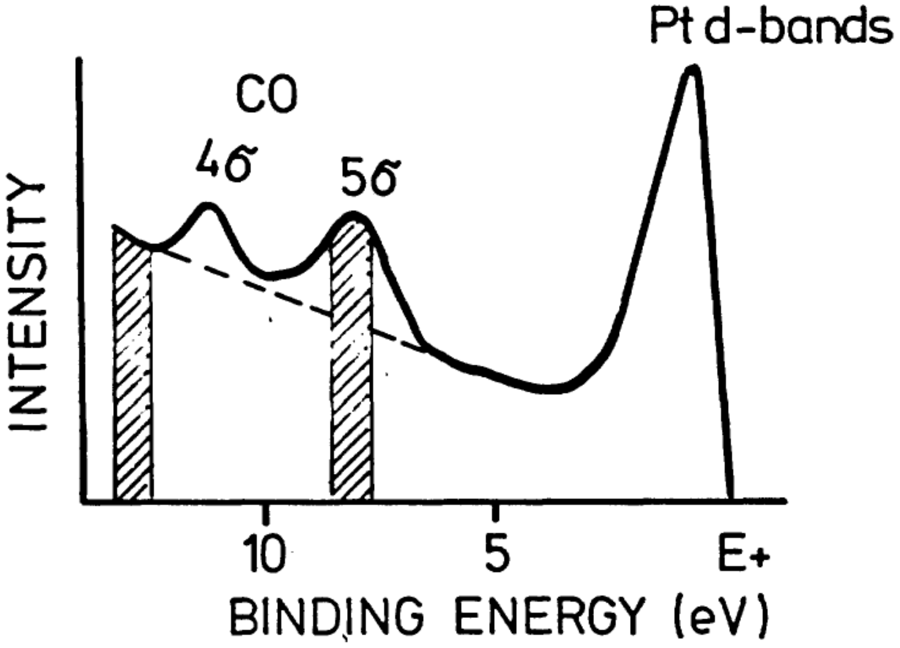
München

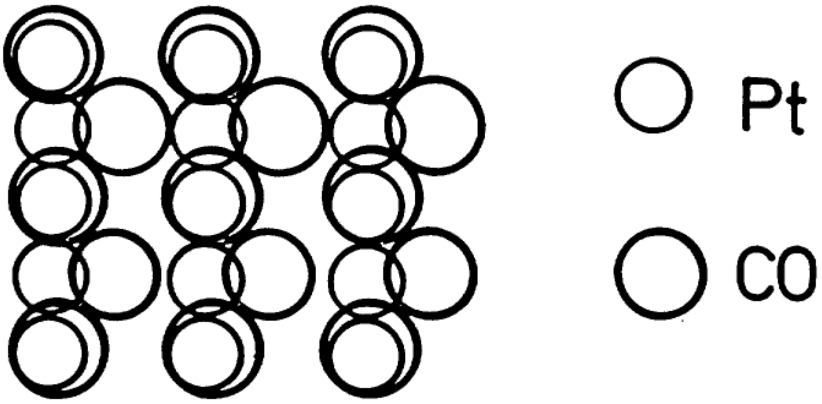
DISPLAY-TYPE ANALYZER

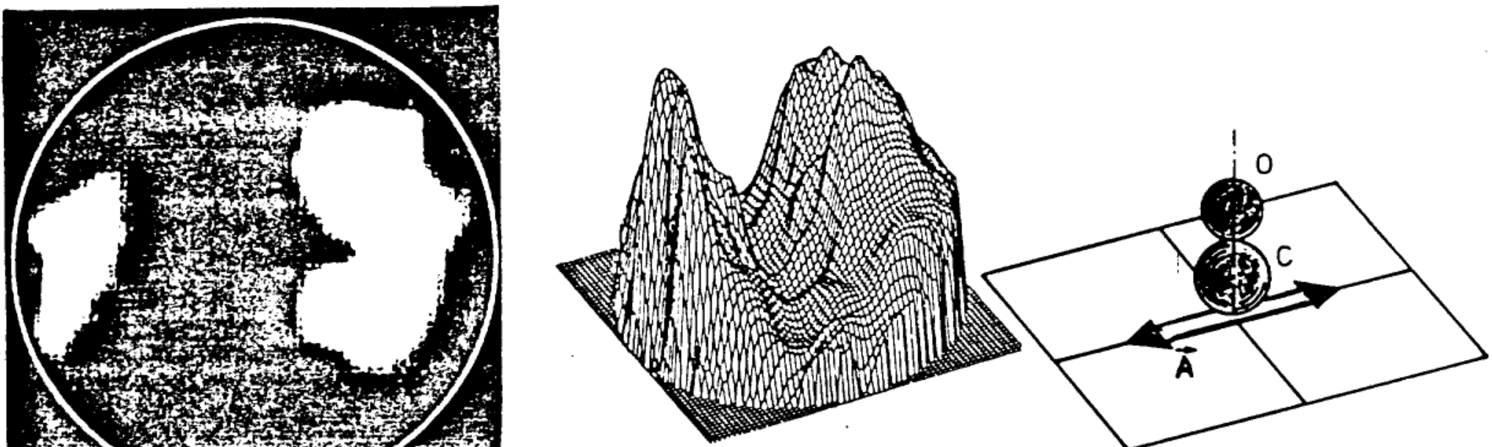


CO / Pt (110)

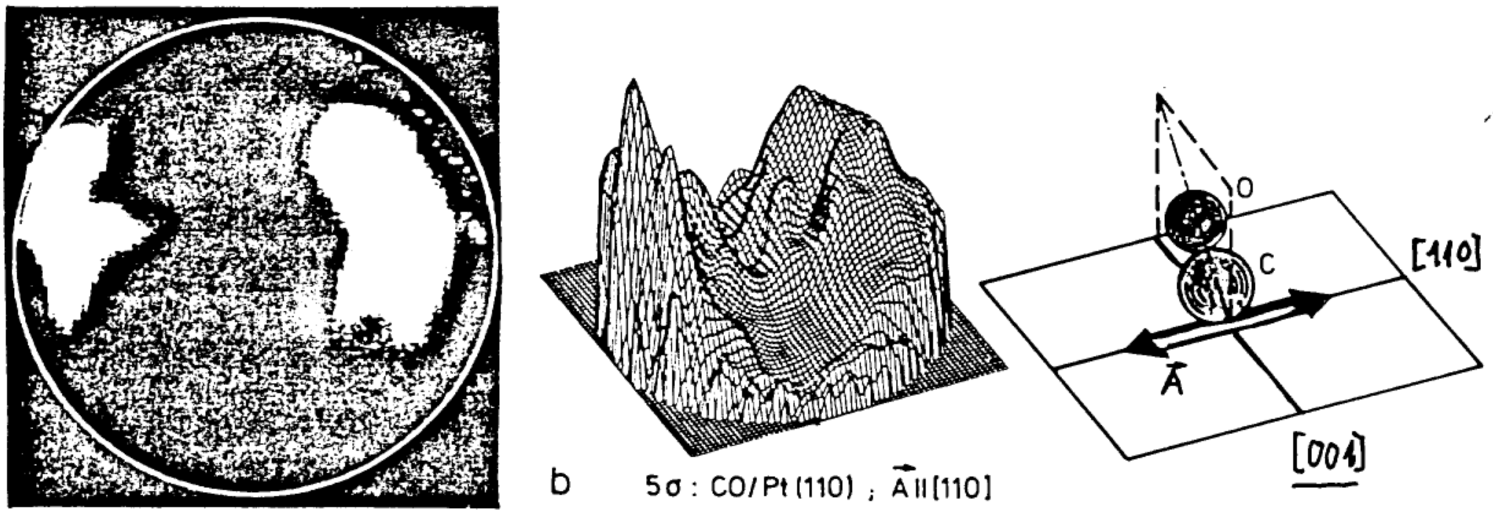
angel integrated EDC



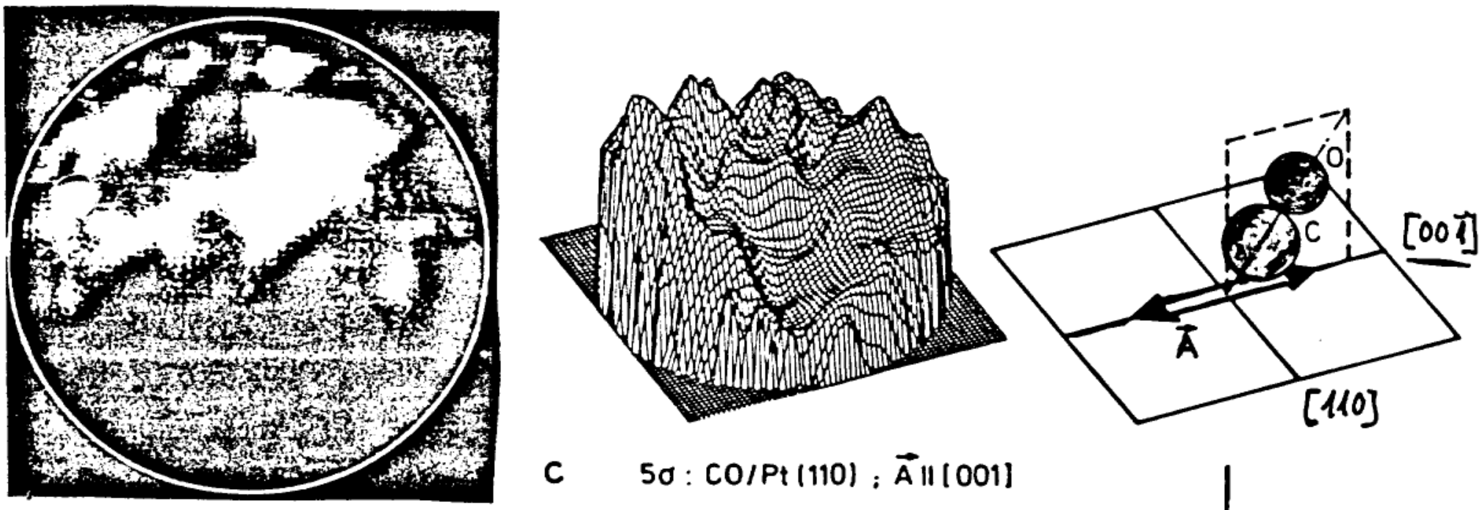

Pt
CO



a 5σ : CO/Pt(111)



b 5σ : CO/Pt(110) ; $\vec{A}$ ∥ [110]



c 5σ : CO/Pt(110) ; $\vec{A}$ ∥ [001]