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Synchrotron Radiation

by

C. Kunz

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Deutsches Elektronen-Synchrotron DESY, 2 Hamburg 52, Germany

Synchrotron radiation is electromagnetic radiation emitted by circular electron or positron machines. Its continuous spectrum extends from the infrared over the visible, the vacuum-ultraviolet for into the x-ray region. Synchrotron radiation has unique properties and is now the most powerful light source for spectroscopy at wavelengths below 2000 Å. Special laboratory arrangements are needed when this by-product of high-energy machines is utilized for atomic, molecular and solid state spectroscopy. The installations at DESY and a few typical experiments are described.

Invited paper presented at the meeting on:
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1. INTRODUCTION

Everybody is familiar with the high-energy particle machines as devices where charged particles are injected into roughly circular orbits from which they are eventually ejected or lost. Another aspect comes into play if we look at a charged particle going around in the orbit from the side. Then the whole structure looks like a huge excited antenna (see Fig. 1). Such an antenna, however, must radiate off energy according to fundamental laws of physics. The spectrum of this electromagnetic radiation will contain the frequency of revolution (typically 1 MHz) and harmonics thereof (multiples of 1 MHz). Indeed, it turns out that so high harmonics are contained in the spectrum that it extends beyond the visible (10^{15} Hz) into the x-ray region (10^{20} Hz). This radiation is called "synchrotron radiation" but it is not unique to synchrotrons and could as well be called "betatron radiation" if this name had been invented.

2. IMPORTANCE FOR HIGH-ENERGY MACHINES

The total intensity radiated can be calculated from classical electrodynamics and is given by:

$$\text{Intensity} \propto \left(\frac{\text{Energy}}{\text{Mass}}\right)^4 \times \frac{\text{Current}}{\text{Radius}}$$

The important parameters are the mass of the particles, their energy, the radius of the orbit and the total current of particles. Immediately a number of conclusions follow from this equation:

(1) For electrons and positrons the radiated power is by thirteen orders of magnitude larger than for protons. Actually the effect is without any practical importance for proton machines.

(2) Synchrotron radiation eventually limits the maximum energy of circular electron and positron machines because of the dependence on the fourth power of the energy. With big accelerators the microwave power needed to make up the losses in particle energy due to this radiation exceeds the energy used for acceleration of the particles. One of the consequences was the building of the biggest electron accelerator, SLAC, as a 2 mile linear accelerator rather than a circular machine.

(3) Large radii of the circular machines are of importance not only because of magnetic field limitations but also because of synchrotron radiation.

The two intersecting storage rings DORIS which are just going into operation at DESY, Hamburg, will radiate more than 1 megawatt of synchrotron radiation altogether. They will be the most powerful source of synchrotron radiation built up to now.

Another aspect of this phenomenon is the possibility to "see" single electrons orbiting in a storage ring. This was observed (probably for the first time) at the PSL storage ring at Stoughton/Wisconsin. Due to the long lifetime of beams in a storage ring a "beam" of one single electron could be generated and could be observed visually for an extended period. One of the reasons why this becomes possible is the repetitive passage of the electron at the point of observation.

Historically[1] the theory of synchrotron radiation was treated first by Ivanenko and Pomeranchuk (1944) in Russia and independently by Schwinger (1946) in the USA. Blewett was the first to observe the effect of the energy loss of the electrons due to the emission of synchrotron radiation on the path of these particles in a betatron (1946). He could not observe the radiation because the vacuum chamber was made out of opaque material. The first direct observation of synchrotron radiation was accidental. A bright light observed through the walls of the transparent vacuum chamber at one of the first synchrotrons was initially attributed to a discharge but then traced back to be synchrotron radiation by Elder, Gurevitch, Langmuir and Pollock in 1947. Only after 1960 a rapid development set in towards using accelerators as sources of radiation for spectroscopic purposes.

3. PROPERTIES

a) Spectrum

Figure 2 shows in a schematic way the dependence of the spectrum on the particle energy in an accelerator like DESY. It extends gradually to shorter and shorter wavelengths with higher and higher particle energies. Finally, at the maximum energy of 7.5 GeV it covers the infrared visible, ultraviolet, vacuum-ultraviolet, soft and hard x-ray regions. Although in principle the spectrum consists of closely spaced lines (harmonics of the frequency of revolution) the lines are so closely spaced and the orbit is irregular enough to result in a completely continuous spectrum. Figure 3 gives the calculated intensity which can be used at the laboratory distance of 40 m from the source at DESY and DORIS in a reasonably dimensioned entrance aperture of a monochromator (2 cm x 2 cm).

Figure 4 demonstrates as an example the advantage of using a source having a continuous spectrum compared to the classical gas discharge or spark sources. Almost none of the fine structure observed previously proved to be genuine to the spectrum of Cr. The solid line shows the results obtained using synchrotron radiation. The fine structure was obviously due to the characteristics of the lamps rather than to the material investigated.

b) Comparison with other sources

(1) In the far infrared (10 - 1000 μm) radiation from storage rings with a current in excess of 1 Amp is superior by roughly one order of magnitude to the radiation of a black-body source. Use of synchrotron radiation in this range is under discussion, it might, however, not become reality because of the rapid development of infrared lasers.

(2) Synchrotron radiation is less intense than readily available lamps in the visible.

(3) At wavelengths below 2000 Å synchrotron radiation is superior to any other source for spectroscopic purposes through its intensity and continuous spectrum. There are, however, a few discrete emission lines available in the vacuum ultraviolet (from gas discharges) and in the x-ray region (from certain x-ray anticathode materials) which could prove to be more useful for some applications.

Although the overall intensity of synchrotron radiation is very large it cannot compete with any laser source at the wavelengths where lasers are available.

c) Collimation

Synchrotron radiation is emitted by the orbiting particle into a very narrow cone around their instantaneous direction of flight. In order to help imagination one could think of the light from cars on a circular race track with their head-lights on. Figure 5 illustrates the pattern of emission. The angular width is wavelength dependend. The following may serve as an example for the good collimation of the beam. A fluorescent screen illuminated at 40 m distance from the source by the x-ray part of the spectrum shows a band only 5 mm high. Compared to classical x-ray tubes synchrotron radiation has within this small angular range a luminosity which is higher by several orders of magnitude.

d) Polarization

Since the emission of synchrotron radiation is analogous to that of an antenna in the plane of the synchrotron it is obvious that the radiation is highly polarized. This polarization can be an important factor for the investigation of anisotropic processes.

e) Vacuum source

In contrast to many other sources in the vacuum-ultraviolet a synchrotron is a very clean source. No gas or other dirt is carried along with the light into the experimental chamber. This is very important since no windows are available in this region.

f) Absolute intensity

Synchrotron radiation is a phenomenon which can be exactly calculated from classical electrodynamics. Experiments have proved that it behaves according to these calculations. Therefore synchrotron radiation can be used as a radiation standard. This is especially important in the vacuum ultraviolet where black-body standards do not emit enough intensity. If the number of orbiting electrons is known the complete radiation pattern can be calculated in absolute terms. This has been used at several places to calibrate secondary standards through which thereafter ocket spectrometers were calibrated.

g) Time structure

The radiation has a very characteristic time structure which is a copy of the time structure of the orbiting electron beam. At DESY the electrons are bunched into packets of about 0.1 nsec length with a repetition frequency of the bunches of 2 nsec. It is under consideration to make use of this structure in order to measure decay times of atomic excitations.

4. SYNCHROTRON RADIATION LABORATORIES

Those accelerators and storage rings where synchrotron radiation is used as a light source are listed in Table 1. Eight years ago only four centers were in existence (Washington, Tokyo, Frascati and Hamburg). There are three stages of development to be observed. Electron accelerators where synchrotron radiation experiments are set up parasitically with a primary interest in high energy physics at the installation ("first generation"), storage rings which have been designed according to the needs of high energy physics ("second generation"); storage rings which are designed and dedicated as light sources from the outset ("third generation"). We are presently at the stage that the first "third generation" facility is under construction in Japan, others are under consideration.

Figure 6 shows the system of high energy electron and positron beams at the DESY synchrotron and storage rings (DORIS). Synchrotron radiation can be obtained everywhere where the beams undergo bending in a magnet. Presently three laboratories are set up another one is under construction. Two of them will eventually be operated by EMBL (European Molecular Biology Laboratory) for the purpose of research on biological objects only.

One of the laboratories is shown in Fig. 7. Ten different experiments are set up in two floors. The light beam is split by grazing incidence glass mirrors into several beams in order to allow for simultaneous operation of different experiments. Presently about 40 scientists, students and technicians are working with synchrotron radiation at DESY. They come as guest workers from about 8 different universities and institutions in Germany and conduct about 10 different experiments. Regularily visiting scientists from abroad are joining the group. A few examples of experiments will be given at the end of this paper.

5. TECHNICAL PROBLEMS

Several technical problems had to be solved in order to use a synchrotron safely and efficiently as a light source:

a) Since no windows are permissible in the vacuum ultraviolet and soft x-ray regions a direct vacuum connection has to be maintained between the experiment and the synchrotron.The danger of vacuum hazards in the experimental chamber ruining the vacuum in the synchrotron arises . Fast acting valves are necessary to protect the accelrator. If gases are under investigation in an experiment, a differential pumping system has to keep the gases from entering the accelerator.

b) Because of radiation safety considerations the laboratory had to be built at a distance of 40 m from the source. Due to the good vertical collimation of synchrotron light this causes only a loss of intensity proportional to the distance rather than the square of the distance as with usual sources. The experiments can be set up while the beam is blocked with a lead beam-shutter. While running, the experiments need to operated by remote control. This is a situation quite common in high-energy physics but spectroscopists had to get used to it.

c) Spectrograph arrangements, to which the light source is attached as a small light weighed component which could be moved together with an entrance slit along a focusing curve,cannot be used at a synchrotron radiation facility. In this respect the situation resembles much more spectroscopy in astrophysics. New designs of specially developed spectrographs became necessary. A typical and very successful monochromator arrangement is shown in Fig. 8. The curved ruled grating focusses the radiating source (the electron beam in the accelerator) on the exit slit. By rotating the grating around an off-center axis the wavelength is changed while focussing is maintained. Such an arrangement gives good intensity down to 400 Å. At shorter wavelengths the reflectivity at normal incidence becomes too low and by far more complicated arrangements with optical components at grazing incidence need to be used.

d) Optical components which are hit directly by the full intensity of synchrotron radiation are damaged more or less rapidly. With the present synchrotrons the vacuum is not completely free from hydrocarbons and a surface contamination of crack-products (carbon) develops which reduces the reflectivity. Grating surfaces which usually are replica in expoxy raisin can develop bubbles. Therefore at the higher intensities of a storage ring light source ultra-high vacuum at the optical components is a necessity. Perhaps even water cooling of mirrors (in the order of 50 Watt of radiation could hit the m) and the use of original gratings ruled in metal has to be considered.

e) With a light source emitting such a broad spectrum as that of synchrotron radiation stray-light from wavelengths other than that selected by a monochromator can be a severe problem. Many special tricks are needed in order to avoid such an unwanted background.

f) Synchrotrons are not very stable in intensity. The number of orbiting electrons is varying from one injection to the next. This is no big problem in high-energy physics experiments, since they count for one point in a curve for a long time. With synchrotron radiation spectroscopy one spectrum could be obtained in 5 minutes. A rapidly reacting faithful monitor is becoming a necessity. Figure 9 shows yield spectra (total number of electrons emitted from a sample as a function of photon energy) of Al_2O_3 with and without monitoring. The curve at the bottom part of the figure is least influenced by the fluctuations. However, its shape is smoothly distorted due to the spectrally varying sensitivity of the monitor. The monitor was a gold coated mirror reflecting the monochromatized beam at a grazing angle toward the sample. Simultaneously this mirror served as the cathode of an open reference multiplier.

In this context only a selection of the special technical aspects of synchrotron radiation could be given. There are many more details which are of interest: alignment of the instruments with the help of x-rays and a laser system, development of radiation filters, special monochromators for the soft x-ray region etc.

6. EXPERIMENTS

Figure 10 gives a survey on the various optical techniques which are used in different spectral regions at DESY. In the following only a small selection of experimental results will be given as an example.

a) Figure 11 shows the reflectivity R and the absorption coefficient μ of Al over a wide energy region. Absorption measurements using synchrotron radiation could fill a large gap in the data on μ for several different materials. From a complete knowledge of such data any optical quantity can be derived. These are e.g. reflectivities under oblique angles of incidence and different polarization, transmissivities of filters, energy loss of fast electrons etc. Such values are of great practical importance e.g. for the design of optical instruments in the VUV region.

b) Figure 12 shows fine structure in the absorption cross section of Na in the metal and in the vapour state. Such rich line structure yields a host of information on the electronic states in atoms and solids. It is a proving ground for modern many-body theories. Similar spectra of organic molecules have been obtained and help to develop theories on molecular states.

c) Even more information on molecules is obtained from an investigation of the decay of excited states. Decay products like ejected electrons, fluorescence radiation or molecular fragments can be analyzed. Figure 13 shows the formation of specific fragments of difluoroethylene as a function of wavelength of the exciting photons. The instrument with which these measurements were obtained consisted of a commercial mass spectrometer in which the ion source was modified for the purpose of photoionization (and fragmentation) rather than by electron bombardment. Curves like those of Fig. 13 permit the evaluation of molecular binding energies.

d) Finally an example from the field of molecular biology may serve to point out the usefulness of the x-ray part of synchrotron radiation. The static structure of the active sub-units of muscular motion (the sarkomeres) is known in considerable detail from electron microscopic picture and x-ray scattering experiments. Such an x-ray Laue picture from which the real structure can be reconstructed takes about 60 hours of exposure using classical sources. The reason is that the intensity of classical x-ray tubes is wasted since the radiation has to be collimated to a very narrow beam. Synchrotron radiation has all its intensity in a narrow beam already. Therefore such pictures were obtained in a few minutes at DESY (Ref. 9). The improvements in intensity with the new storage rings together with apparative developments will allow for taking such picutures in a few milliseconds. This, however, is the time during which muscular motion occurs. The future goal of these experiments is to follow the changes of structure during the muscular contraction process. By means of synchrotron radiation this could become reality.

General Information for further reading

1. A.A. Sokolov and J.M. Ternov, Synchrotron Radiation, Oxford Pergamon Press, 1968, 207 p. (translated from the Russian)
2. R.P. Madden and K. Codling, Instrumental Aspects of Synchrotron XUV Spectroscopy, Applied Optics 6, 31, 1967
3. R. Haensel and C. Kunz, Experimente mit Synchrotronstrahlung, Z. für angew. Physik 23, 276 (1967)
4. R.P. Godwin, Synchrotron Radiation as a Light Source, Springer Tracts in Mod. Phys. 51, 1, 1969
5. C. Gähwiller, F.C. Brown and H. Fujita, Extreme Ultraviolet Spectroscopy with the Use of a Storage Ring Light Source, Rev.Sci.Instr. 41, 1275 (1970)
6. W. Hayes, Spectroscopy with a Synchrotron Light Source, Contemp. Phys. 13, 441 (1972)
7. G.V. Marr, J.M. Munro and J.C.C. Sharp, Synchrotron Radiation: A Bibliography, Daresbury Nuclear Physics Laboratory 1972
8. K. Codling, Applications of Synchrotron Radiation, Rep. Progr. Phys. 36, 541 (1973)
9. F.C. Brown, Ultraviolet Spectroscopy of Solids with the Use of Synchrotron Radiation, in Solid State Physics, ed. by H. Ehrenreich, F. Seitz and D. Turnbull (1974)
10. J.O. Jackson: Classical Electrodynamics (John Wiley, New York 167, Chap. 14)

References and Footnotes

1. References of the first publications are given in the review articles listed above. The author is indebted to Professor Blewett and Professor McMillan for clarifying some historical details in a discussion subsequent to the presentation of this talk.

2. B. Sonntag, Thesis, Hamburg 1969

3. C. Kunz in Band Structure Spectroscopy of Metals and Alloys, Ed. D.J. Fabian and L.M. Watson (Academic Press, London 1973), p. 503

4. M. Skibowski and W. Steinmann, J.Opt.Soc.Am. 57, 112 (1967)

5. W. Gudat, C. Kunz and J. Karlau, Appl.Optics 13, No. 8, in press

6. H.-J. Hagemann, W. Gudat and C. Kunz, DESY SR-Report, to be published

7. H.-W. Wolff, K. Radler, B. Sonntag and R. Haensel, Z. Physik 257, 353 (1972)

8. D. Reinke, R. Krässig and H. Baumgärtel, Z. Naturforsch. 28a, 1021 (1973)

9. G. Rosenbaum and K.C. Holmes, Nature 230, 434 (1971)

Table 1: Accelerators and storage rings used as light sources

Project	E(GeV)	R(m)	I(mA)	λ_c (Å)	Remarks
NBS(Washington)	0.18	0.83	10	800	Conversion to storage ring planned
INS-SOR(Tokyo)	1.3	4.0	50	10	
Frascati	1.1	3.6	14	15	
DESY(Hamburg)	7.5	31.7	10-30	0.42	
Wisconsin Storage Ring PSLI	0.24	0.64	20	220	exclusively used as a light source
Glasgow	0.33	1.25	0.1	195	operation finished
Bonn I	2.3	7.65	30	3.5	
Bonn II	0.5	1.7	30	76	
Moscow I	0.68	2	10	35.6	
Moscow II	1.36		10		planned for 1973/4
Erewan ACU	6.0	24.65	22	0.64	
NINAI(Daresbury)	4.0	20.8	40	1.8	
CEA (Cambridge/Mass.)	6.0	26.0	30	0.7	operation finished cycling or storage mode
PTB(Braunschweig)	0.14	0.46		937	
ACO(Orsay) Storage Ring	0.55	1.1	100	30	
SPEAR(Stanford)	2.5	12.7	45	4.5	
Storage Ring SSRP	(3.5)	12.7	(58)		( )after July 1974
IMS-SOR(Tokyo) Storage Ring	0.3	1	100	200	planned for exclusive use as light source starting ~1973/74
DESY(Hamburg Storage Ring (DORIS	1.75 3.5	12.12	1000 200	12.7 1.58	SR-Lab under Construction
DCI	1.8	3.8	250	3.8	planned for 1973/74
PSL II	1.76	4.5	100	4.61	proposed
Daresbury II	2.0	5.55	1000	3.88	proposed
VEPP-2 Novosibirsk	0.68			23	
VEPP-3 Novosibirsk	2.0			250	under construction
SURF Gaithersburg	1.8	0.83		795	
Cornell	20	120	5	0.084	

Figure Captions

Fig. 1 Particle accelerator as antenna.

Fig. 2 Dependence of the spectral distribution on particle energy (schematic)

Fig. 3 Number of photons available in a 2 cm x 2 cm aperture at laboratory site (40 m distance) at DESY and DORIS (6 Amp at 1.75 GeV is a design value which might not become reality because of beam instabilities)

Fig. 4 Absorption spectrum of Cr in the region of 3p transitions. Solid line values obtained with synchrotron radiation (from Ref. 2)

Fig. 5 Spatial distribution of synchrotron radiation

Fig. 6 System of high energy particle beams at DESY and DORIS. Three places are marked where synchrotron radiation laboratories are set up

Fig. 7 The arrangement of the first synchrotron radiation laboratory at DESY (from Ref. 3)

Fig. 8 Normal incidence Wadsworth-type monochromator (from Ref. 4)

Fig. 9 Simultaneous recording of the yield spectrum of Al_2O_3 without (top) and with monitors (middle and bottom). The best cancellation of fluctuations occurs with a special monitor (bottom) which, however, distorts the spectrum smoothly (from Ref. 5)

Fig. 10 Techniques used at DESY in the different spectral regions

Fig. 11 Reflectivity R and absorption coefficient μ of Al as obtained with the help of synchrotron radiation measurements together with data from the literature in adjacent regions (from Ref. 6)

Fig. 12 Fine structure in the absorption spectrum of Na in the solid and in the vapour phases (from Ref. 7)

Fig. 13 Intensity of different ionized fragments of difluorethylene as as function of the exciting wavelength (from Ref. 8)

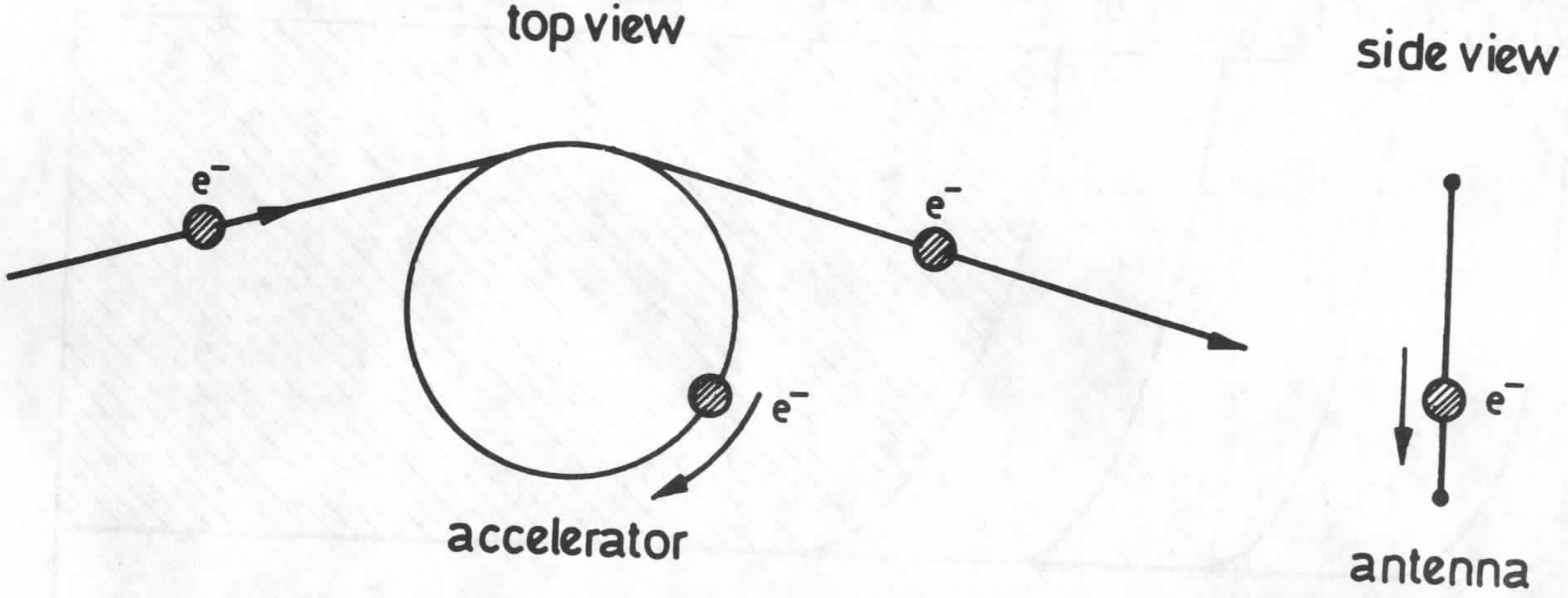


Fig. 1

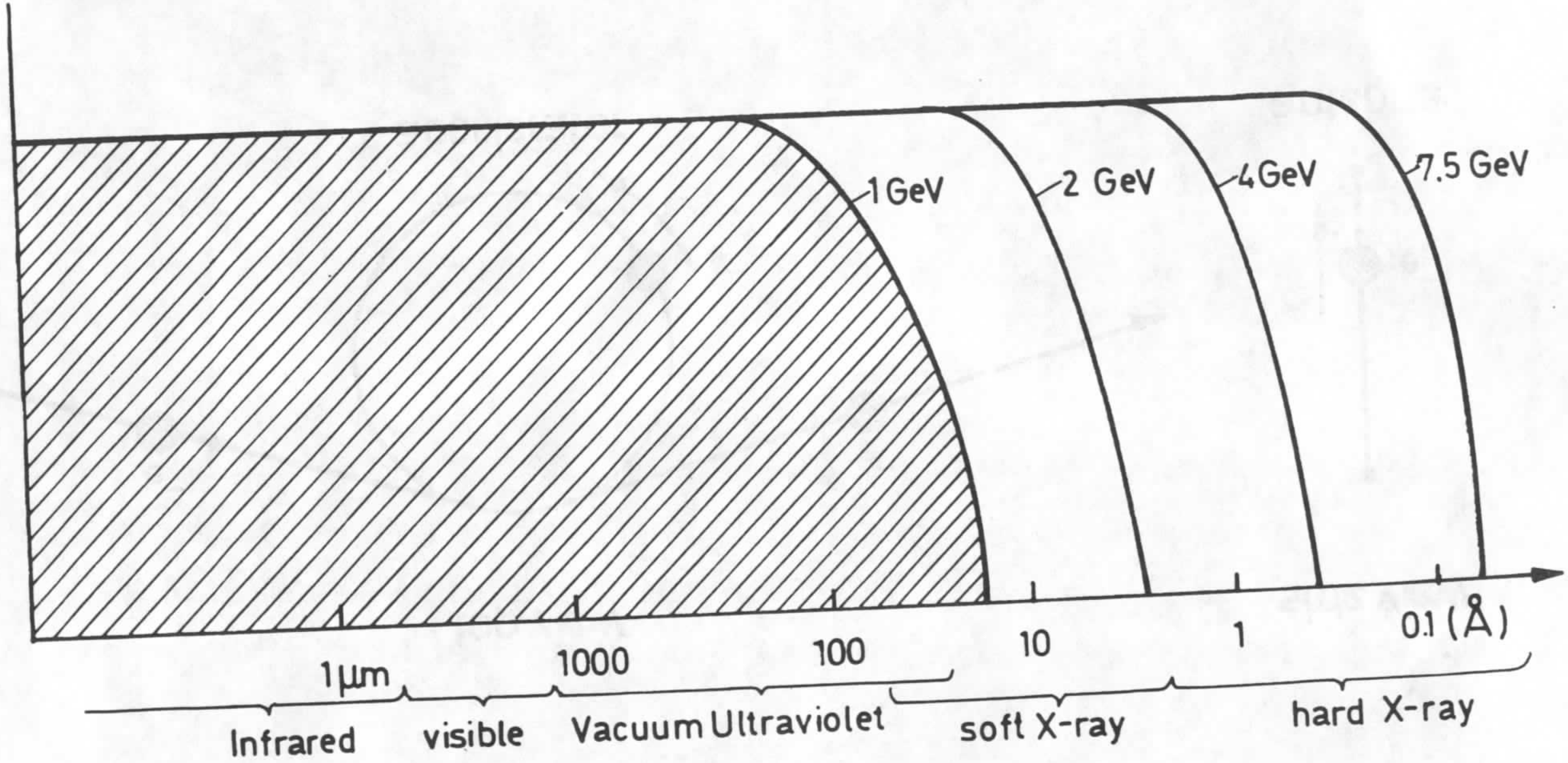

1 GeV
2 GeV
4 GeV
7.5 GeV
1 µm
1000
100
10
1
0.1 (Å)
Infrared
visible
Vacuum Ultraviolet
soft X-ray
hard X-ray

Fig. 2

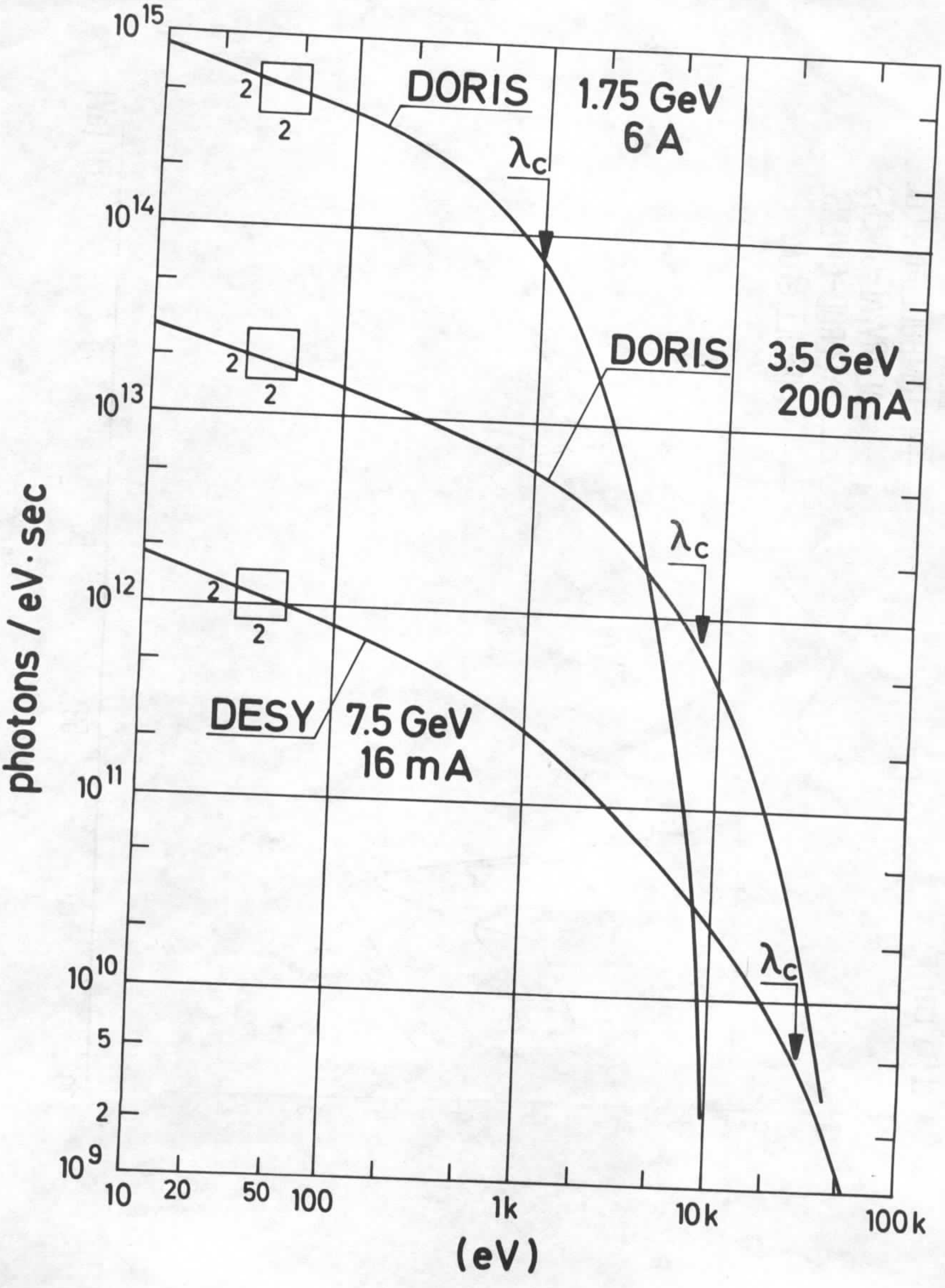

DORIS
1.75 GeV
6 A
DORIS
3.5 GeV
200mA
DESY
7.5 GeV
16 mA
λ_c
λ_c
λ_c
2
2
2
2
2
2
photons / eV · sec
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
5
2
10^{9}
10
20
50
100
1k
10k
100k
(eV)

Fig. 3

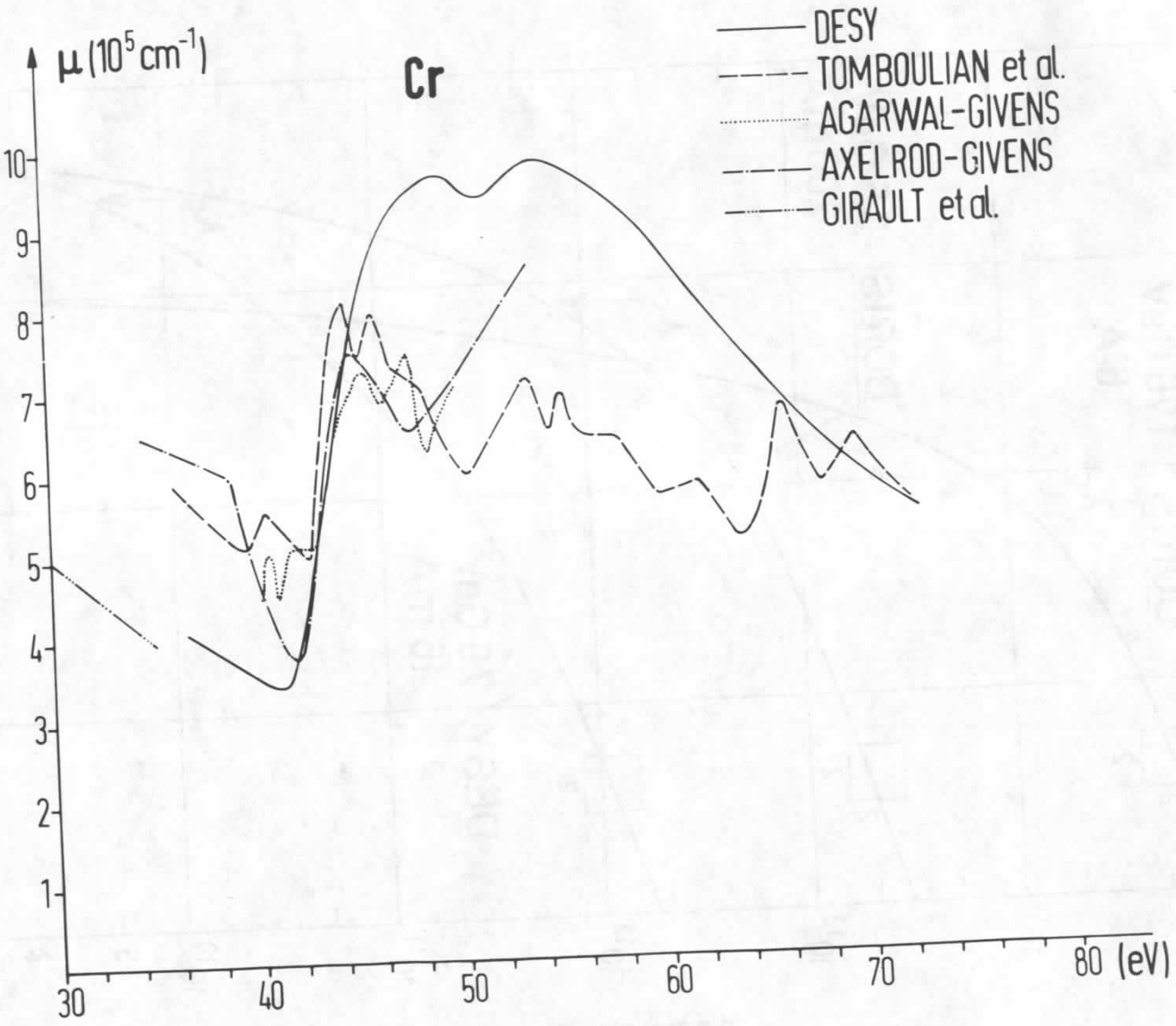

μ (10^5 cm^-1)
Cr
DESY
TOMBOULIAN et al.
AGARWAL-GIVENS
AXELROD-GIVENS
GIRAULT et al.
10
9
8
7
6
5
4
3
2
1
30
40
50
60
70
80
(eV)

Fig. 4

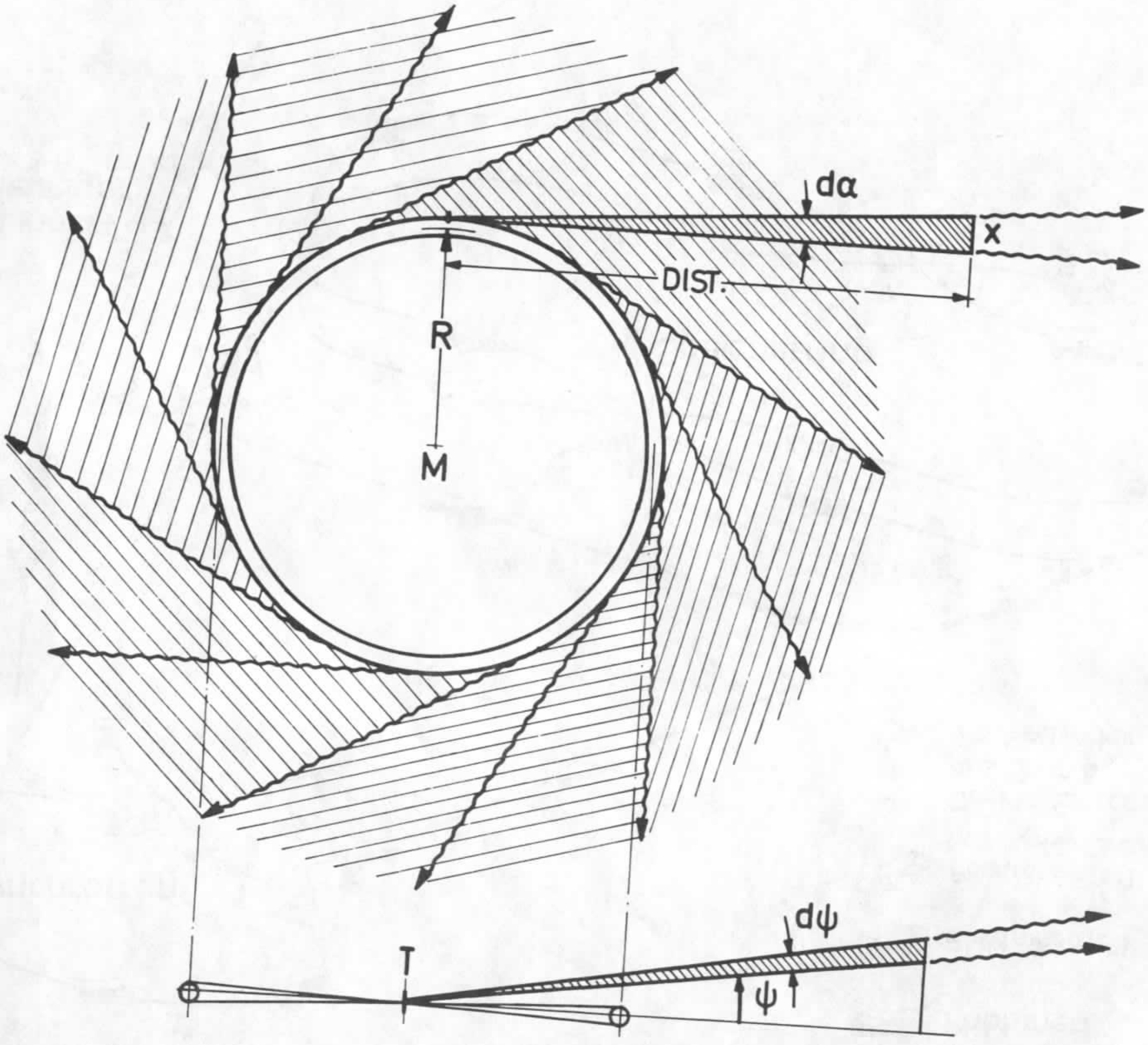


Fig. 5

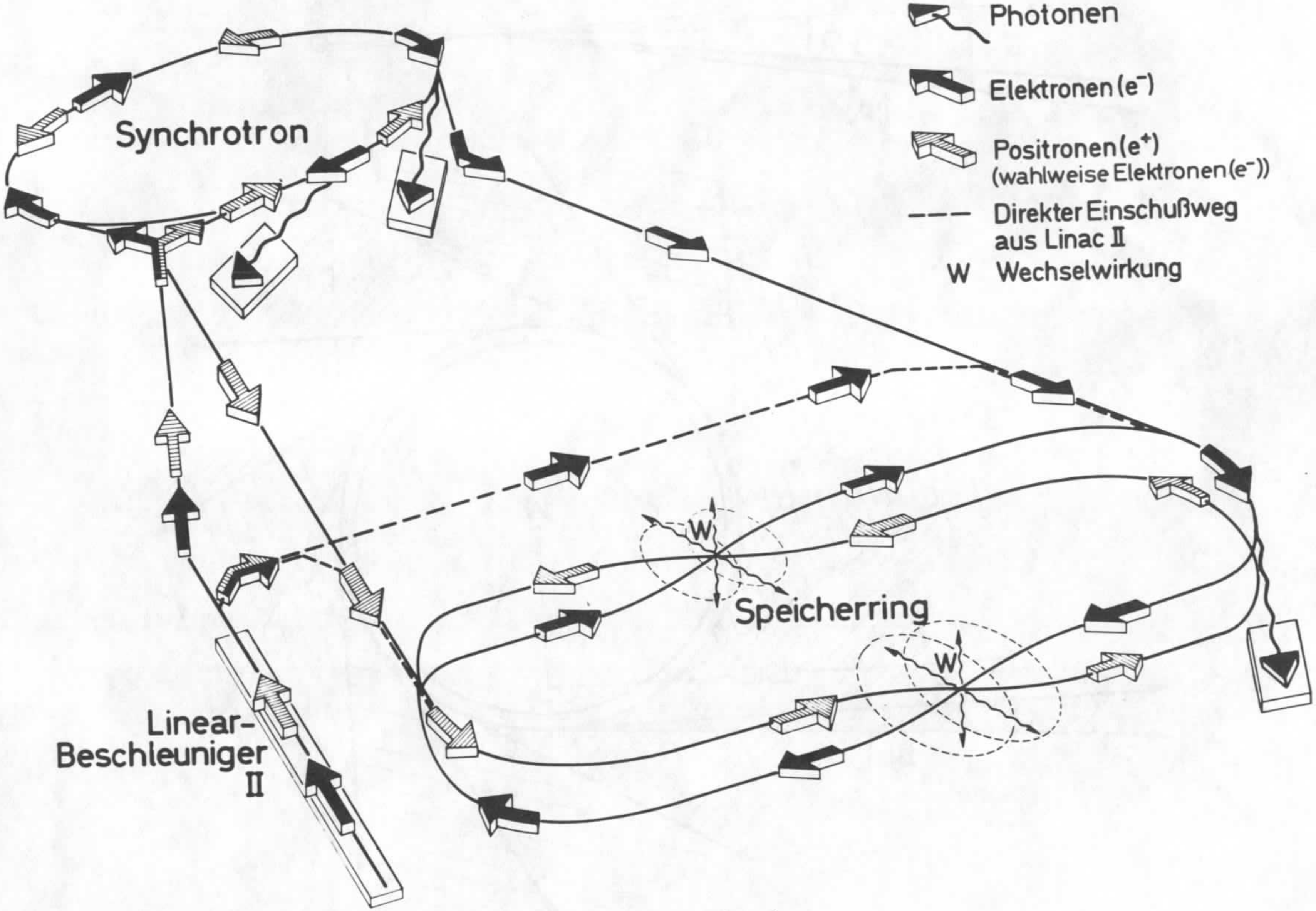

Photonen
Elektronen (e⁻)
Positronen (e⁺)
(wahlweise Elektronen (e⁻))
Direkter Einschußweg aus Linac II
W Wechselwirkung
Synchrotron
Speicherring
W
W
Linear-Beschleuniger II

Fig. 6

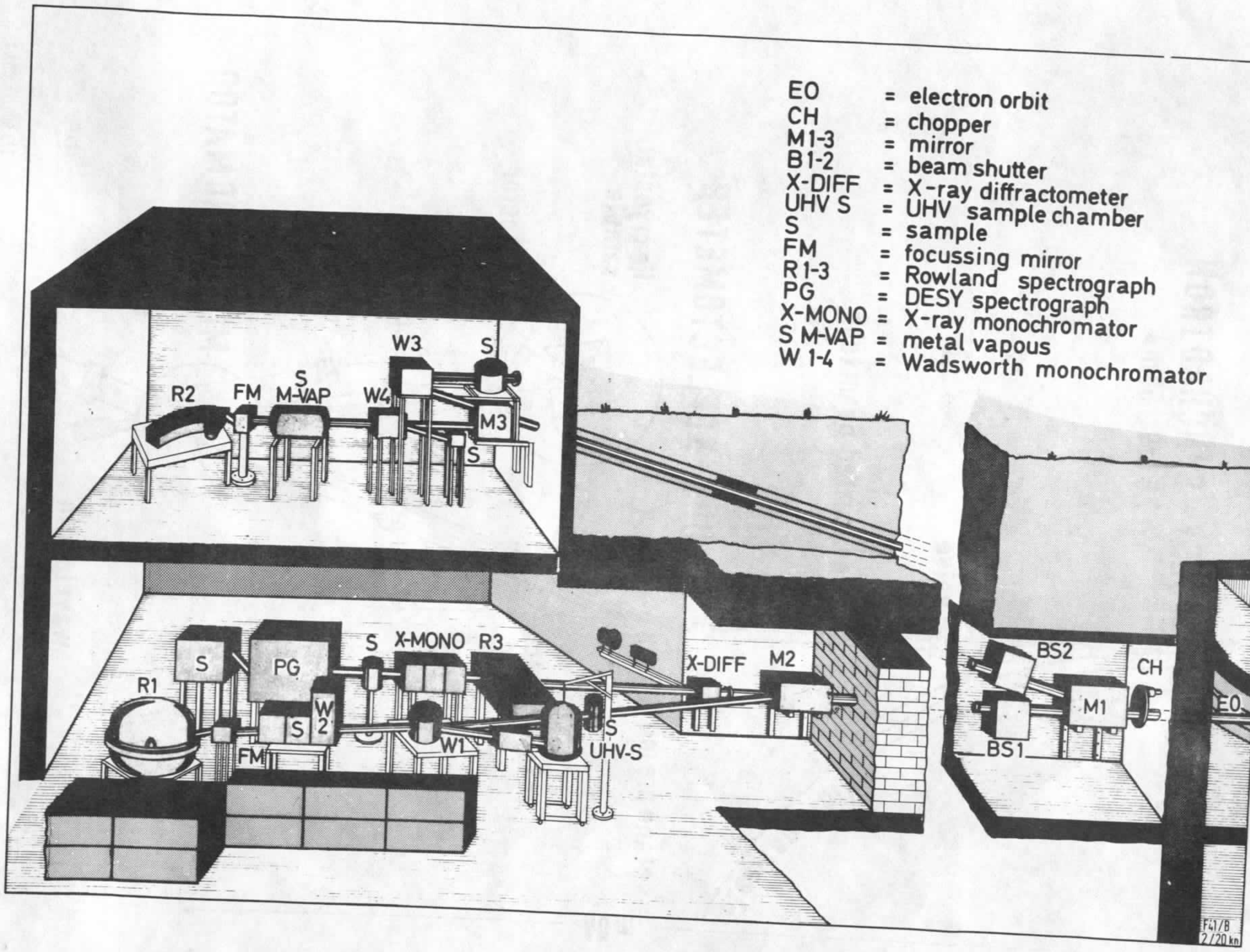
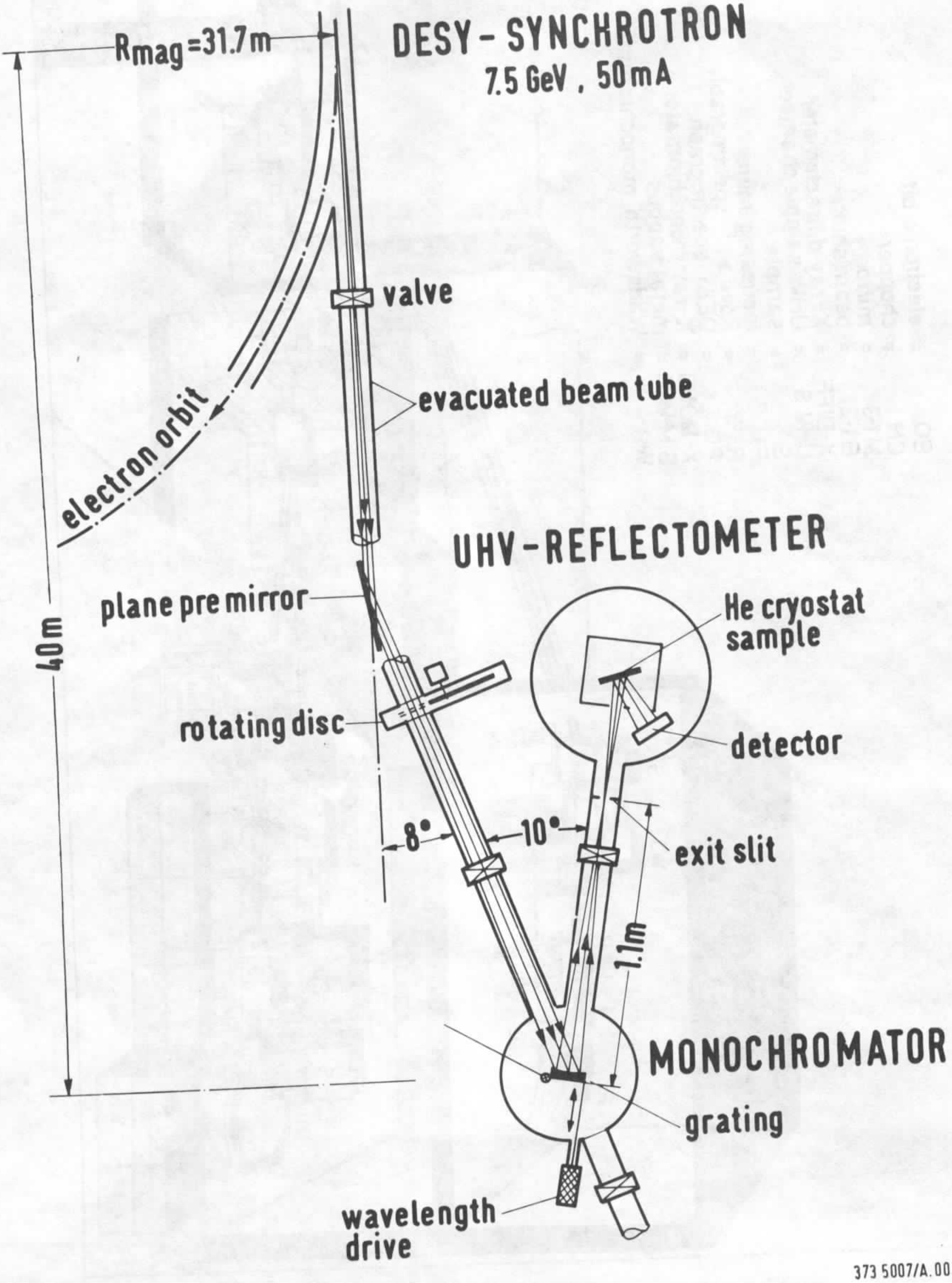

EO = electron orbit
CH = chopper
M1-3 = mirror
B1-2 = beam shutter
X-DIFF = X-ray diffractometer
UHV S = UHV sample chamber
S = sample
FM = focussing mirror
R1-3 = Rowland spectrograph
PG = DESY spectrograph
X-MONO = X-ray monochromator
S M-VAP = metal vapous
W 1-4 = Wadsworth monochromator
R2
FM
S M-VAP
W4
W3
S
M3
S
S
PG
S
X-MONO
R3
R1
W 2
S
FM
W1
S
UHV-S
X-DIFF
M2
BS2
CH
M1
EO
BS1
F41/B 2/20 kn

Fig. 7



373 5007/A.002/7.3

Fig. 8

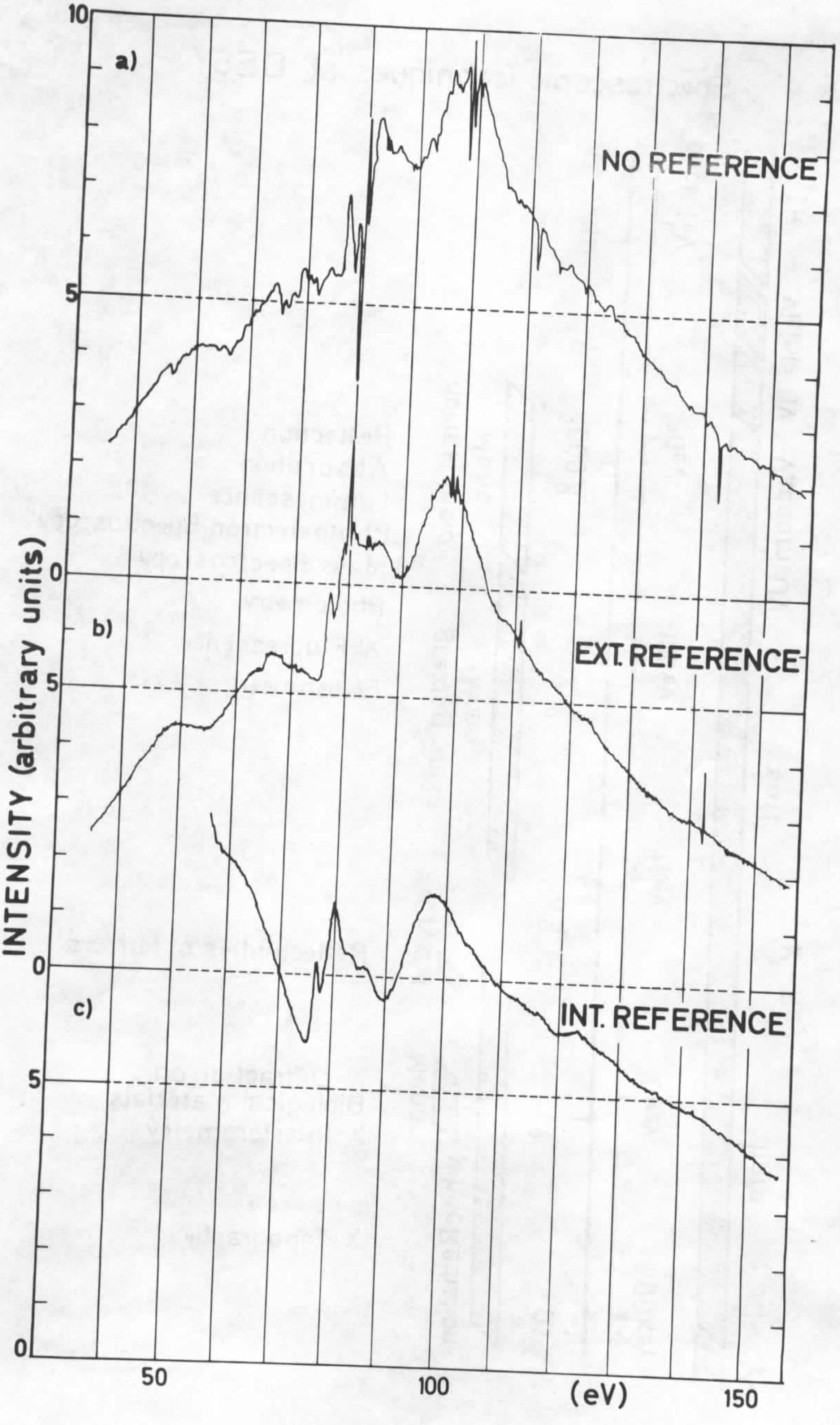
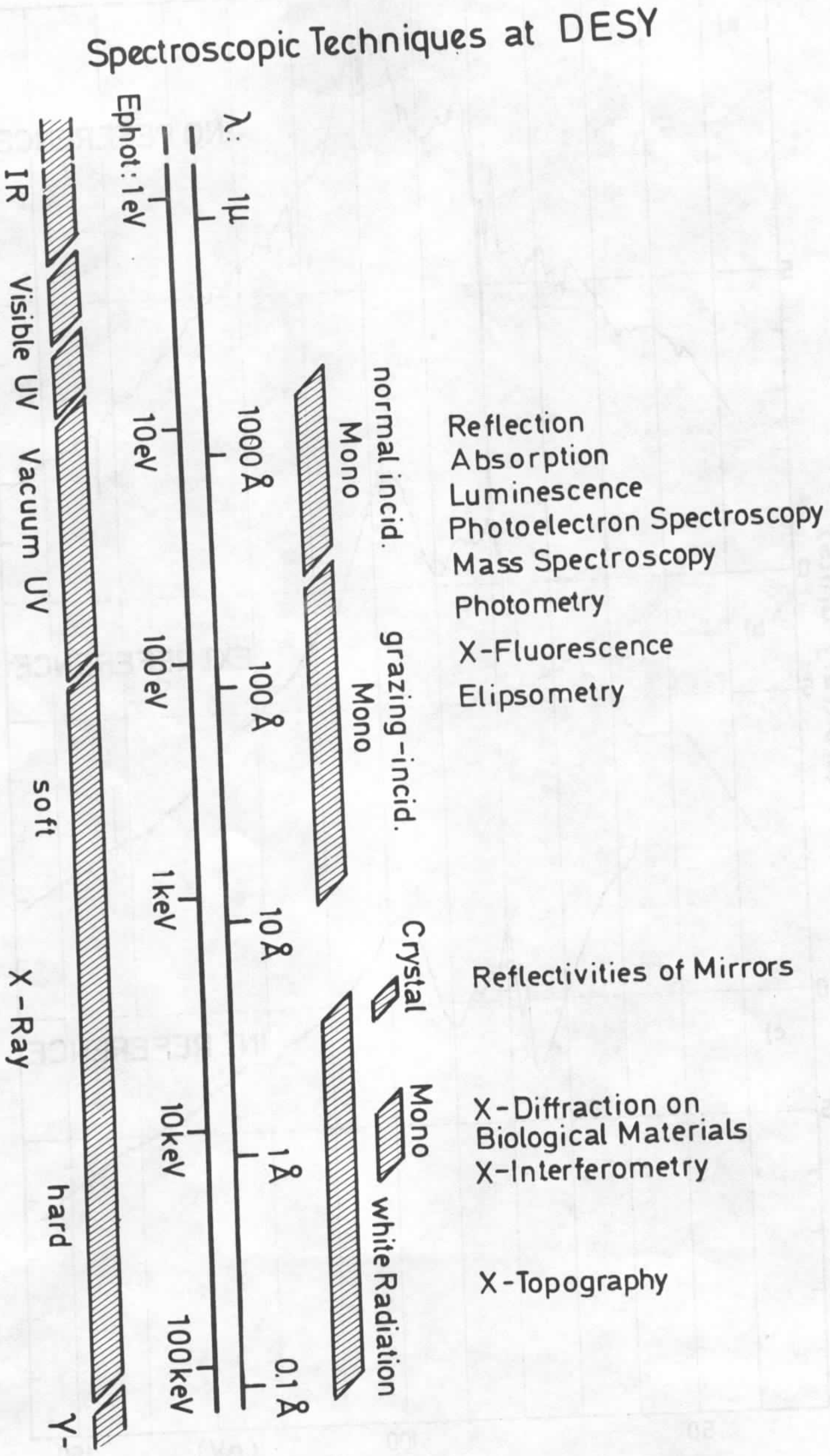

INTENSITY (arbitrary units)
10
5
0
5
0
5
0
a)
b)
c)
NO REFERENCE
EXT. REFERENCE
INT. REFERENCE
50
100
150
(eV)

Fig. 9



Spectroscopic Techniques at DESY
λ:
1μ
1000 Å
100 Å
10 Å
1 Å
0.1 Å
Ephot: 1eV
10eV
100eV
1keV
10keV
100keV
IR
Visible
UV
Vacuum UV
soft
X-Ray
hard
γ-
normal incid.
Mono
grazing-incid.
Mono
Crystal
Mono
white Radiation
Reflection
Absorption
Luminescence
Photoelectron Spectroscopy
Mass Spectroscopy
Photometry
X-Fluorescence
Elipsometry
Reflectivities of Mirrors
X-Diffraction on
Biological Materials
X-Interferometry
X-Topography

Fig. 10

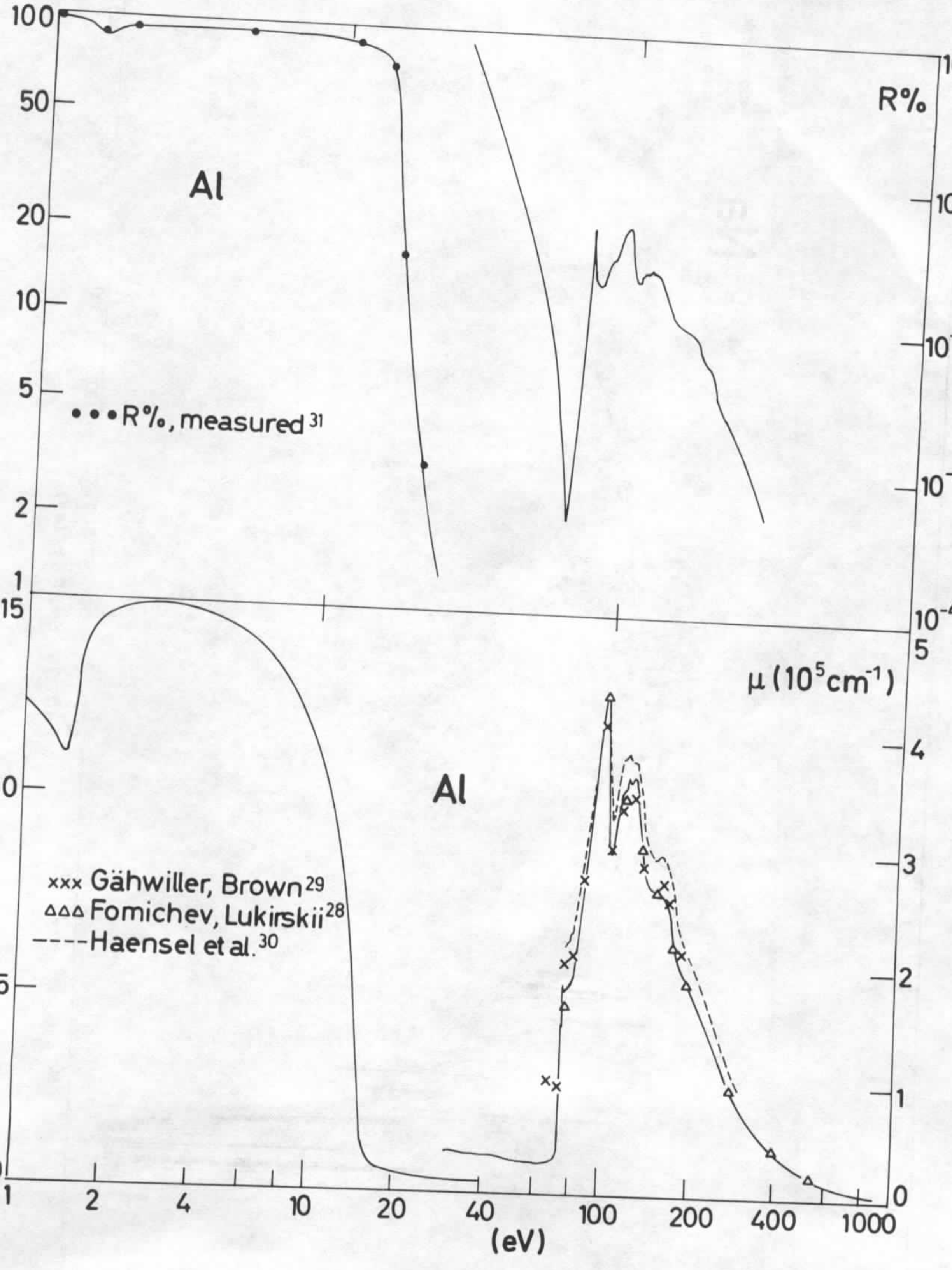

100
50
20
10
5
2
1
Al
R%
10^0
10^-1
10^-2
10^-3
10^-4
• • • R%, measured 31
15
10
5
0
5
4
3
2
1
0
μ (10^5 cm^-1)
Al
××× Gähwiller, Brown 29
ΔΔΔ Fomichev, Lukirskii 28
- - - Haensel et al. 30
1
2
4
10
20
40
100
200
400
1000
(eV)

Fig. 11

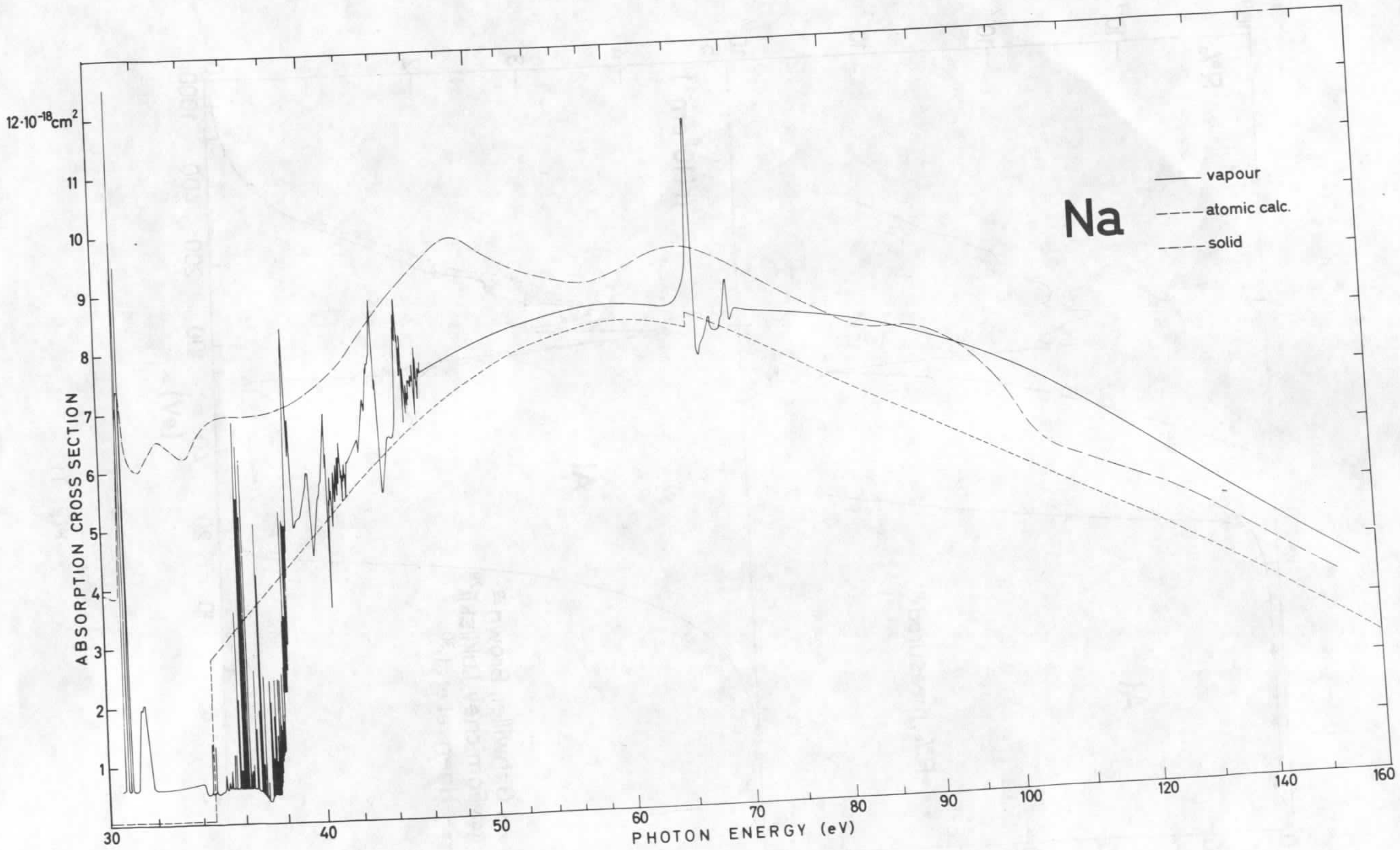
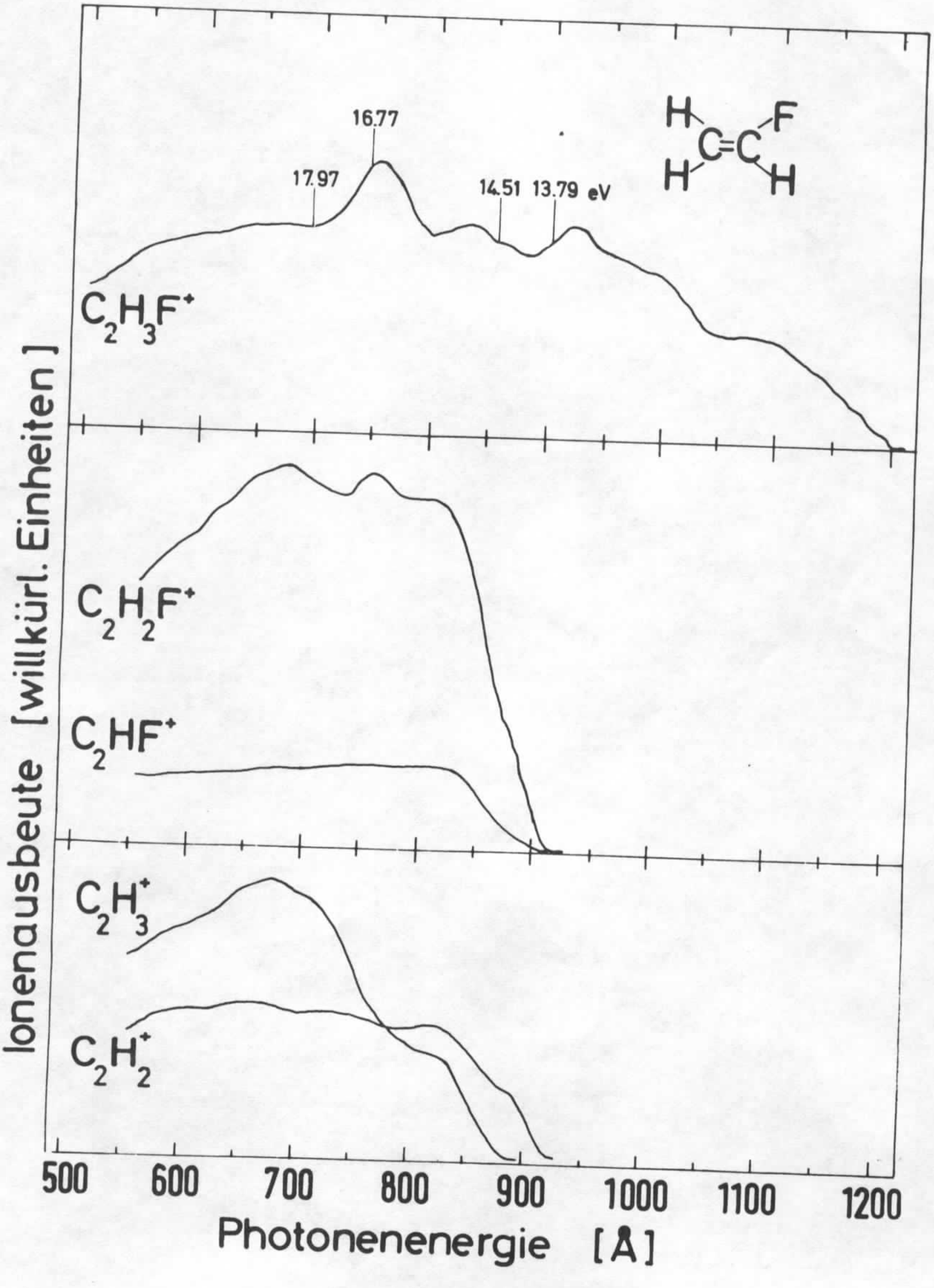

12·10⁻¹⁸cm²
11
10
9
8
7
6
5
4
3
2
1
ABSORPTION CROSS SECTION
30
40
50
60
70
80
90
100
120
140
160
PHOTON ENERGY (eV)
Na
vapour
atomic calc.
solid

Fig. 12



16.77
17.97
14.51
13.79 eV
H
H
C=C
F
H
$C_2H_3F^+$
$C_2H_2F^+$
C_2HF^+
$C_2H_3^+$
$C_2H_2^+$
Ionenausbeute [willkürl. Einheiten]
500
600
700
800
900
1000
1100
1200
Photonenenergie [Å]

Fig. 13