the lifetimes and intensities of positrons annihilating in polysyrene (to be reported[10]) will be summarized in support of the above discussion. We find three components in this glass. I_1 ($\simeq 35\%$) is due to free positrons not trapped or in some short-lived bound state ($\simeq 20\%$) and p-Ps ($\simeq 15\%$). I_2 ($\simeq 27\%$) is due to the annihilation of free positrons in regions of order due to nodules[11] or spherically symmetric strain fields.[12] I_3 ($\simeq 38\%$) is due to the annihilation of positrons in the amorphous regions by pickoff of o-Ps. A plot of τ_3 ($\simeq 2$ nsec) versus the temperature T shows a linear relationship with positive slope, changing to a steeper positive slope at the glass transition.[6] A plot of τ_2 ($\simeq 0.4$ nsec) versus T shows a linear relation with positive slope, similar to τ_3 versus T, below the glass transition where τ_2 changes abruptly from about 0.42 to 0.47 nsec. Thus the glass transition seems to consist of a combination of first-order and second-order transitions. The lifetime of the τ_1 component changes abruptly from 0.13 nsec in the glass to about 0.16 nsec in the highly viscous liquid. While results for temperatures below the glass transition were easily fitted by our model, results for temperatures above the glass transition (highly viscous liquid) were difficult to fit, although the data fit three components better than two or four. Experiments to measure the temperature dependence of positron lifetimes and intensities in polyethylene and to continue the electric field experiments for polar molecules, such as Teflon, are planned.

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Close Similarity between Photoelectric Yield and Photoabsorption Spectra in the Soft-X-Ray Range

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Because of the similarity between photoelectric yield and photoabsorption spectra in the soft x-ray region, "yield spectroscopy" can be used as a successful method for investigating fine structure in the electronic excitation spectra of solids. The continuous spectrum of synchrotron radiation is especially appropriate for such measurements. We reinvestigated the structure of the 4d excitations in Pr and the 2p excitations of Si using a single crystal.

Using the continuous spectrum from a soft-x-ray tube, Lukirskii and co-workers[1,2] established a close similarity between photoelectric yield and absorption spectra for core excitations in several materials, mainly alkali halides. There are, however, only a few yield measurements available which allow a comparison in the low-energy region. Good agreement is found for the $L_{2,3}$ spectrum[3] of Na in NaCl around 30 eV. At even lower energies the $3p$ excitations of K in the potassium halides[4,5] around 20 eV can be identified in both absorption (ϵ_2) and yield spectra; the actual shape, however, of the structure is quite distorted in the yield spectra. The valence-band

spectra at the onset of transitions appear to be different in yield and absorption.[4,5] Few yield investigations have been performed on clean metal and semiconductor surfaces. An unpublished yield measurement[6] on an oxide-free Al surface agrees well with the known $L_{2,3}$ absorption spectrum. This indicates that the similarity between the two types of spectra is not restricted to insulators.

Synchrotron radiation[7] with its intense continuous spectrum covering the whole ultraviolet and soft-x-ray region is especially suited for "yield spectroscopy." In order to further explore the possibilities of this method we have performed photoelectric yield measurements with a variety of insulators, semiconductors, and metals. For LiF, e.g., we were able to confirm the published results[2] and found excellent agreement in all the details of the structure with more recent absorption measurements[8,9] in the 60–150 eV range. We were able to reproduce the absorption spectrum[10] of CsI between 50 and 170 eV (with the Cs and I $N_{4,5}$ structures) and saw the increase in the absorption coefficient[11] of CdSe (below 110 eV) and of PbS (below 80 eV). We similarly found the rapid increase in the absorption[12] of Ag below 120 eV together with some fine structure around 70 eV. Measurements on Ce, Pr, and a single crystal of Si will be discussed at the end of this paper. The present investigations were of an exploratory nature and will be followed by detailed measurements under ultrahigh-vacuum conditions at a later stage. All these results prove that in the extreme uv region yield spectroscopy is a powerful tool for the investigation of absorption structure having all the advantages of using bulk samples, e.g., single crystals.

Although we are aware that the general theory of photoemission is complicated, and that especially the processes involved during the migration of electrons to the surface are not very well understood, the following simplified considerations appear to give a reasonable explanation of the yield spectra. After the primary absorption of a photon, three processes mainly contribute to the photoelectric yield: (1) direct excitation into the conduction band, (2) Auger emission of electrons, and (3) decay of excitons into one-electron excitations.

The fast electrons originating from these processes undergo inelastic electron-electron scattering with the probability of multiplication, the multiplication factor $\eta(\epsilon)$ being a monotonic increasing function of the electron energy ϵ. The

main contribution to the yield should come from electrons with energies a few electron volts above the vacuum level because in the spectral region, which interests us, the mean free path for inelastic scattering increases with decreasing energy, whereas the escape probability through the surface barrier increases from the vacuum level to higher energies. This should result in an effective escape depth D determined by the mean free path of these electrons. D is on the order of 30 Å for metals (see, e.g., Kanter[13]) and several times larger for insulators in the region where electron-electron scattering is impossible. D is small compared to the penetration depth of light in our region of interest; as a result, the total yield Y, defined as the number of emitted electrons divided by the number of incident photons (near normal incidence the reflectivity is negligibly small), is given by

$$Y \propto \mu(E)D[\,p_1\eta(\epsilon_1) + p_2\eta(\epsilon_2) + p_3\eta(\epsilon_3)\,], \qquad (1)$$

$\mu(E)$ being the absorption coefficient of the photons; p_1, p_2, and p_3 being the relative contributions of the processes (1) to (3); and E being the photon energy. Apart from the ϵ-dependent bracket, Y is proportional to $\mu(E)$. Since the electron energies ϵ_i are determined by the photon energy E, the bracket term will become a monotonic increasing function of E. We presume that the function will be structureless due to the averaging over a series of statistical scattering processes which are involved in the determination of $\eta(\epsilon)$. Without going into the details of Eq. (1) for insulators, semiconductors, and metals we would like to mention two points: (a) As has been noted before by Lukirskii et al.,[2] the Auger part of Eq. (1) (apart from the region where it competes with excitonic decay) should be a true replica of $\mu(E)$. (b) Core excitons which predominantly decay into one-electron excitations are by no means suppressed in the yield spectra.

Our experiments were performed by making use of synchrotron radiation emitted by the 7.5-GeV electron accelerator DESY. The continuum was monochromatized by a special monochromator,[14] giving a light beam virtually free from higher-order radiation at a fixed exit slit in the energy region 35 to 300 eV. The resolution $E/\Delta E$ ranges from 400 to 650. Behind the exit slit the light was reflected at a grazing angle of 4° by a gold-coated mirror which, at the same time, was the cathode of an open multiplier (Bendix). The signal from this multiplier served as the reference for the yield measurements. The spec-
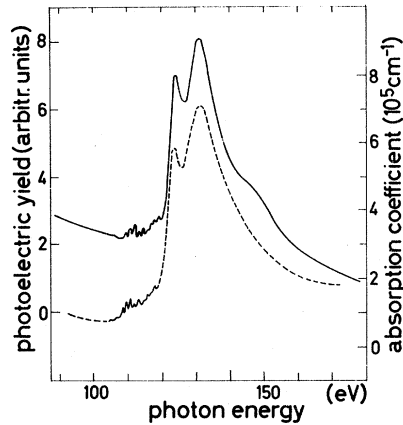
FIG. 1. Comparison of photoelectric yield (solid curve) and absorption (dashed curve) spectra for Pr.
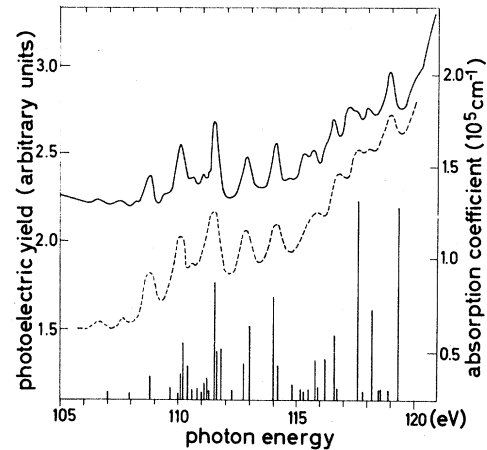

FIG. 2. Energy region of fine structure, yield (solid curve) and absorption (dashed curve) for Pr. The vertical lines are the result of an atomic calculation (Ref. 19); the length of the lines represents the oscillator strength.

trum, as measured by this detector, is smooth with the exception of small fine structure at the Au $N_{6,7}$ edges around 85 eV originating from the gold coating of all the optical components and a pronounced structure at the carbon K edge at 280 eV originating from hydrocarbon contamination on the optical surfaces. The reflected light beam hits the samples at normal incidence. The emitted electrons are accelerated onto the cathode of an open multiplier (Johnston). The signal of this multiplier is electronically divided by the reference signal. The spectra obtained in this way can differ from the actual yield by a factor varying smoothly with photon energy. We call the spectra thus measured "yield spectra."

Figures 1 and 2 show the yield and the absorption spectra[15-17] of Pr in the region of $4d$ transitions. Since the samples were not prepared *in situ* they will be covered by some layer of oxide. For Pr it has been shown before that the absorption spectra of oxide and metal agree with each other. The yield and absorption spectra show very good agreement. (The broad bump at 150 eV also shows up in the absorption spectrum of Ref. 16.) In the yield spectrum the underlying continuum of transitions from higher shells is more pronounced, compared to the fine structure, than in the absorption spectrum. Similar behavior was observed with most of the other materials mentioned above and should be explainable from a detailed consideration of Auger and other excitations for the transitions from different shells for each individual material according to Eq. (1). An equally good agreement between the yield and the absorption spectrum was obtained from measurements on Ce.

More details of the fine structure are observed

in the yield spectra when compared to the absorption spectra primarily as a result of a better signal-to-noise ratio. This advantage is inherent in yield spectroscopy. A theoretical explanation of the structures in the rare-earth metals was achieved by Dehmer *et al.*[18] and Sugar[19] on the basis of atomic calculations. Because of exchange interaction the $4d^9 4f^{N+1}$ final-state configuration splits into a series of widely spread sublevels. The numerical calculations performed for Ce and Pr show good agreement, also for the additional lines not found in the absorption spectra, both in position and strength of the lines (see, e.g., Fig. 2).
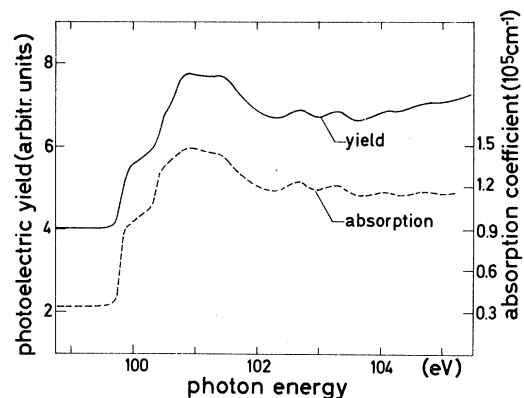
In addition we performed measurements on a

FIG. 3. Comparison of the photoelectric yield measured on a cleaved Si single crystal surface (solid curve) and the absorption coefficient (dashed curve) of a polycrystalline Si film, after Brown and Rustgi (Ref. 20).

Si single crystal cleaved in air immediately be-
fore mounting. The result is shown in Fig. 3 and
is compared with the absorption measurements
performed by Brown and Rustgi[20] on a polycrys-
talline sample. Small differences could be main-
ly attributed to a lower resolution in our case.
The main features, however, are present in both
spectra. The rise of the yield at the high-energy
end of the spectrum is due to the first peak in the
spectrum[21] of SiO_2 at 106 eV since our sample
was not completely free from oxide. (This was
even more pronounced when using a polished
single crystal.) When measurements under ultra-
high-vacuum conditions become possible, the in-
vestigation of single crystals by yield spectros-
copy will certainly be of primary interest.

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Magnetic Field Effect on Plasma-Wave Dispersion in a Dielectric Layer

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We present dispersion curves and field amplitudes for a plasma layer in a magnetic
field. Various effects such as the nonreciprocal character of the dispersion, the pileup
of bulk states at ω_∞, and the existence of surface states above ω_∞ should be observable
in optical experiments.

The recent measurements of the surface plas-
ma dispersion relation in InSb by Marschall,
Fischer, and Queisser,[1] are in good agreement
with predictions derived by treating the semicon-
ductor as a dielectric half-space.[2] However, the
dispersion relation in this case is a single, struc-
tureless curve asymptotic at small frequency to
the light-line ($\omega = kc$) and at large ω to the sur-
face plasma frequency $\omega_s = \omega_p[\kappa/(\kappa + 1)]^{1/2}$, κ being

the high-frequency dielectric constant of the lat-
tice. A more exacting test of the dielectric mod-
el can be made if the system is perturbed by the
introduction of a magnetic field permeating the
sample, and a finite thickness is considered for
the dielectric.

The effect of a magnetic field on the optical con-
stants deduced from bulk properties has been dis-
cussed by Palik and Wright.[3] The modes dis-