COLLECTING EFFICIENCY OF A CYLINDRICAL MIRROR ELECTRON ENERGY ANALYZER WITH PRE-RETARDING LENS

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ABSTRACT

The electron collecting efficiency of a cylindrical mirror energy analyzer incorporating retardation of the electrons prior to analysis has been determined over the range 0 to 30 eV by two methods. The first method requires the use of a vacuum ultraviolet monochromator to produce monoenergetic electrons of different energies; the second method involves measuring the energy-brightness relationship of the retarding optics and should be applicable to any deflection analyzer with pre-retarding optics. The results of the two methods are compared and the limitations of the latter method are discussed.

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INTRODUCTION

We have previously described a cylindrical mirror electron energy analyzer with a pre-retarding lens, for use in determining photoelectron branching ratios.[1] Included was a brief description of the measurement of the electron collecting efficiency of the analyzer. Knowledge of this electron collecting efficiency (the transmission of the analyzer combined with the efficiency of the detector) is extremely important for accurate measurement of the relative populations of final states by photoelectron spectroscopy. In this paper we describe a more accurate determination of the collecting efficiency of the analyzer extended over the range 0 to 30 eV using the technique previously described, which requires the use of a number of different photon energies selected with a vacuum ultraviolet monochromator. In addition, we present a second method for determining the collection efficiency, which is a simplified version of the method described by Poole, et al.[2] Only one photon energy is required and thus an undispersed light source may be used.

The analyzer is shown schematically in fig. 1. Electrons ejected in a small cone about 54° 44' to the axial photon beam pass through a pair of slits normal to the electron beam direction and may be retarded or accelerated before passing into the deflection region. The analyzer is designed for first-order slit to slit focusing on the inner cylinder and the beam is baffled to accept a 6° cone at the detector end. Spectra are normally recorded in the constant resolution mode, that is, the voltage on the retarding/accelerating slits is swept and the deflecting field is held constant so that only electrons exiting from the lens with the required pass energy reach the detector.

CROSS-SECTION METHOD

The geometry of this analyzer is such that electrons of different angular distributions are not discriminated against, nor are they discriminated against for varying polarization of the incident photon beam.[3] Thus, if the gas pressure in the source region is held constant and electron scattering from the gas is not significant, it follows that the rate at which electrons are detected, N_d, is given[1] by

$$N_d \propto I_0 \sigma \gamma C(E),$$

where I_0 is the incident photon flux, σ is the absorption cross section of the gas, γ is the ionization yield, and C(E) is the collection efficiency of the analyzer. For the rare gases, γ is unity in the photon energy range covered here, (for wavelengths shorter than the onset of double ionization, the yield is greater than unity). Thus, C(E) is determined on a relative basis, as a function of the initial electron kinetic energy and for a given pass energy, by recording photoelectron spectra from a rare gas at a variety of wavelengths of measured intensity at which the photoabsorption cross section is known.

The calibration results for a number of different ion chambers, obtained with a spark discharge light source (and corresponding weak analog signals) have been presented elsewhere.[1] The present calibration was performed with a duoplasmatron light source dispersed with a 1/2 m Seya-Namioka monochromator, producing a number of Ar II emission lines continuous in time so that electron counting techniques were possible. The intensity of the light source was monitored on an aluminum photocathode, calibrated against a tungsten standard, positioned at the rear of the ionization region. Photoelectron spectra were recorded from both argon and xenon, with relevant cross sections taken from the literature.[4] The intensities of the $^2P_{3/2}$ and $^2P_{1/2}$ peaks in argon were summed at each wavelength and the electron energy was taken as a mean of the peaks weighted by the statistical weight for 3/2:1/2 spin-orbit splitting. For xenon, separate curves were plotted for the $^2P_{3/2}$ and $^2P_{1/2}$ peaks. The $^2P_{3/2}$ to $^2P_{1/2}$ intensity ratio in each of the rare gases has been shown to be constant in the wavelength range covered here.[5] A number of runs were made for a pass energy of 3 eV and then normalized to give the data shown in the range 0 to 11 eV in fig. 2.

To extend the energy range of the calibration, a Vodar type grazing incidence monochromator was used to disperse the radiation from a DC discharge in helium. A number of photoelectron spectra were recorded from argon at 584, 537, and 304 Å and from neon at 537, 304, and 256 Å. The resulting collection efficiency data were normalized to the 0 to 11 eV region and averaged to produce the data points at 19, 25, and 27 eV in fig. 2

The relative collecting efficiency as a function of the initial electron kinetic energy was determined by the cross section method for different pass energies. The curves for the different pass energies could all be normalized to agree with the 3 eV pass energy data of fig. 2 for electron energies greater than 0.7 eV. The variation in collecting efficiency in the low energy region for the different pass energies was measured by comparing photoelectron spectra recorded from oxygen with dispersed 736 Å Ne I radiation. The spectrum provides a source of electrons of reasonable intensity over the range 0 to 4.8 eV. The results are plotted in fig. 3 for pass energies of 0.75, 1.0, 1.5, 2.0, and 2.5 eV, all relative to the intensities of spectra recorded at a pass energy of 3 eV. These results were in agreement with those obtained by comparing spectra of the B $^2\Sigma_g^-$ state of O_2^+ at 584 Å taken at different pass energies. The curves for the different pass energies depart only for electron energies less than 0.7 eV. The analyzer becomes much more efficient for low energy electrons as the pass energy is lowered, with the efficiency peaking about 0.2 eV.

The collecting efficiency was monitored as a function of time by periodically recording the oxygen spectrum at 736 Å at a pass energy of 3 eV. No significant changes in the relative population of the peaks were detected, indicating that the surfaces of the analyzer, coated with colloidal graphite, did not change sufficiently to affect the electron collecting efficiency.

The collecting efficiency of the analyzer for zero acceleration/retardation in the lens (where the spectrum is scanned by varying the volatage across the cylinders) was also measured by the cross section method. The pressure in the analyzer was held below 10^{-4} Torr to reduce differential scattering effects, which are more serious in this mode of operation.[1] The cone voltage of the channeltron detector was held at 400 V to minimize effects caused by the changing electron energy at the detector. Peak heights (or, equivalently, peak areas divided by the electron energy) were used in recording the photoelectron intensities. The results for the range 0 to 9 eV are plotted in fig. 4. As determined previously,[1] low energy electrons are severely discriminated against in this mode of operation. The primary cause of the roll-off at low energies is apparently electrostatic (contact potentials or non-uniform surface potentials) since small changes in the magnetic field (but large enough to effect the resolution) did not significantly alter the shape of the curve.

PASS CURVE METHOD

Poole, et al.[2] recently proposed a technique for measuring the effect of a retarding lens on the transmission of an energy analyzer, which is summarized as follows. Photoelectron spectra were recorded from a number of gases at a number of undispersed wavelengths. The count rate for a given initial electron energy at each wavelength was measured as a function of the pass energy by varying the degree of acceleration or retardation in the lens. Then the assumption was made that the transmission of the deflection region of the analyzer was constant when the electrons had zero acceleration in the lens and that the efficiency of the detector was constant. Thus, a family of curves of collecting efficiency vs. pass energy for electrons of different initial kinetic energies was generated, all normalized (to unity) at the point where the pass energy equalled the initial electron energy. These curves were then interpolated to find the collecting efficiency as a function of the electron energy for a given pass energy and this data was used to correct a spectrum recorded at that pass energy by scanning the voltage on the lens. Kemeny, et al.[6] subsequently derived expressions which explained the transmission data obtained as just described in terms of the energy-brightness law for their analyzer geometry.

We wish to show here that the technique of Poole, et al. can be simplified and that only one source of electrons is required to determine the transmission of the lens/analyzer combination. Further, the limitations of this technique can be seen by comparing the results obtained with those from the cross section method.

The collecting efficiency of a lens/analyzer combination will be a function of both the pass energy E_p and the initial electron kinetic energy E_k. From conservation of flux and Abbe's sine law,[7] we see that the transmission of the lens section is separable into independent functions of the kinetic energy that the electron has on either side of the lens. The electrons in this case enter the lens with energy E_k and exit from the lens with energy E_p. Once out of the lens, the transmission through the deflection region and the detection efficiency will depend only on E_p. It follows that the collecting efficiency of the lens/analyzer combination can be separated into independent functions of the two variables. That is,

$$C(E_k,E_p) = g(E_k)\cdot f(E_p). \tag{1}$$

E_k and E_p (in electron volts) are connected by the relation

$$E_p = E_k + V_{ar} , \tag{2}$$

where V_{ar} is the accelerating potential applied across the lens, and may be positive or negative.

Consider now the collecting efficiency when $E_k = E_p$, i.e., when the voltage across the lens elements is zero. Equation (1) becomes

$$C(E,E) = f(E)\cdot g(E), \tag{3}$$

so that the function g(E) is given by

$$g(E) = C(E,E)/f(E). \tag{4}$$

Inserting equation (4) into equation (1) yields

$$C(E_k,E_p) = \frac{C(E_k,E_k)\cdot f(E_p)}{f(E_k)} . \tag{5}$$

If the spectrum is recorded at a fixed pass energy, the function $f(E_p)$ is a constant. Hence

$$C(E_k,E_p) \propto \frac{C(E_k,E_k)}{f(E_k)} \tag{6}$$

The function $C(E_k,E_k)$ depends on the transmission through the analyzer and on the detection efficiency. The transmission through the analyzer is generally assumed to depend only on the geometry and the detector efficiency is assumed to be constant. If these assumptions are true, then $C(E_k,E_p)$ becomes the transmission function of the lens alone and essentially represent the change in the brightness of the beam as the electron energy changes in the lens.[2,7,8] This energy-brightness relationship depends on the source dimensions and will in general be difficult to calculate exactly. However, the relationship may be determined experimentally, at least over a limited energy range.

Assuming C(E,E) to be constant, the function f(E) is readily measured by plotting a curve of the count rate of photoelectrons from any one source, at one wavelength, as a function of the pass energy by varying V_{ar}. This was done for Xe photoelectrons at 584 Å over the range 0 to 40 eV. The pressure in the analyzer was held below 10^{-4} Torr to minimize differential scattering effects. The results at pass energies greater than 12 eV showed a strong dependence on the voltage on the cone of the channeltron detector. The electrons focus on the inner cylinder of the analyzer and the cone voltage deflects them into the detector. However, little change was observed for cone voltages above 1400 V and the results taken with an EMI venetian blind multiplier with the front dynode at 1400 V agreed with the channeltron data. The curve of count rate vs. pass energy for the $^2P_{3/2}$ electrons (energy 9.09 eV) is plotted in fig. 5.

The data of fig. 5 was least squares fitted with a power law function, with the result that the function f(E) has an $E^{0.50}$ dependence over this energy range. This curve is also plotted in fig. 5. Data were also recorded for Xe $^2P_{1/2}$ electrons at 920 Å (energy 0.04 eV) and the count rate showed the same functional dependence on the pass energy. We note that for a line source where the lens produces focusing in one dimension only, the brightness is proportional to $E^{1/2}$. The photon beam in our analyzer enters along the axis and if few off-axis electrons pass the system of baffles, we might expect the $E^{1/2}$ dependence shown in fig. 5. However, the count rate data of fig. 5 show a systematic departure from the $E^{1/2}$ curve, probably caused by the collection of off-axis electrons. In a similar analyzer in this laboratory in which the photon beam enters normal to the axis, the source is smaller and more uniform and the count rate shows a linear dependence on the pass energy, cf. the results of Poole, _et al._[2] These results are explained by the brightness of the electron beam being proportional to E for a lens which focuses in two dimensions.[7]

Measurement of the function C(E,E) by the cross section method is described above. It is clear from fig. 4 that C(E,E) is not constant for electron energies less than 4 eV, but does become constant at greater energies. Thus, we may reasonably predict from equation (6) that for electron energies greater than 4 eV, the relative collecting efficiency of the analyzer at any fixed pass energy will be given by the inverse of the function plotted in fig. 5.

COMPARISON OF THE TWO METHODS

The function f(E) plotted in fig. 5 was inverted and normalized to the relative collecting efficiency for a pass energy of 3 eV (fig. 2) at 5 eV. The two curves are plotted for comparison in fig. 6. The agreement between the curves is excellent in the range 2 to 20 eV.

Agreement below 2 eV is not expected since the function C(E,E) from fig. 4 is clearly not constant in this range. However, multiplying the functions of figures 2 and 5 together to form C(E,E) by equation (3) does not produce the function shown in fig. 4 for the relative collecting efficiency when the voltage across the lens is zero. It is thought that losses in the analyzer, responsible for both the reduced efficiency at low electron energies compared with that predicted by the inverse of the pass curve and the roll-off in the collecting efficiency for zero volts across the lens, are different for the two cases because of field penetration through the lens into the ionization region. The results shown in fig. 3 for the different pass energies are also indicative of different field penetration into the source.

The disagreement above 20 eV is probably caused by poor collection of the diverging electron beam at the channeltron. In addition to the difficulties noted above when measuring the pass curve, the relative collecting efficiency between 5.5 and 25.0 eV was found to be a function of the channeltron cone potential, even though the electrons were being analyzed at a fixed pass energy of 3 eV. The relative efficiency varied by 20% as the cone potential was raised from 100 to 1400 V. Although the electrons originally formed with different energies have the same energy at the exit slit on the inner cylinder, the beam divergence will be different because of the action of the lens. Thus the beam will cover different regions of the cone; the gain of these detectors has been shown to vary greatly across the face of the cone.[9] Since the analyzer was designed for a first order focus, the changing divergence could be expected to have little effect on the resolution; no change in the FWHM of the detected peak was noticed for the two different energies.

CONCLUSION

The collecting efficiency properties of a cylindrical mirror analyzer incorporating a pre-retarding lens have been described in detail. The simplified method presented for the determination of the collecting efficiency has been shown to give good agreement with the more basic cross section method, with the exceptions noted. The agreement at the higher energies could possibly be improved by redesigning the analyzer to focus the electrons on the axis, close to the cone of the detector. This simplified method should be applicable to the measurement of the relative collecting efficiency of any lens/analyzer combination, provided precautions are taken to minize differential detection effects.

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FIGURE CAPTIONS

1. Schematic cross section of the analyzer. A-inner cylinder; B-collimating slit; C, D-retarding slits; E-boron nitride insulator; F-photocathode; G-collimating slit; H-detector; I-outer cylinder.

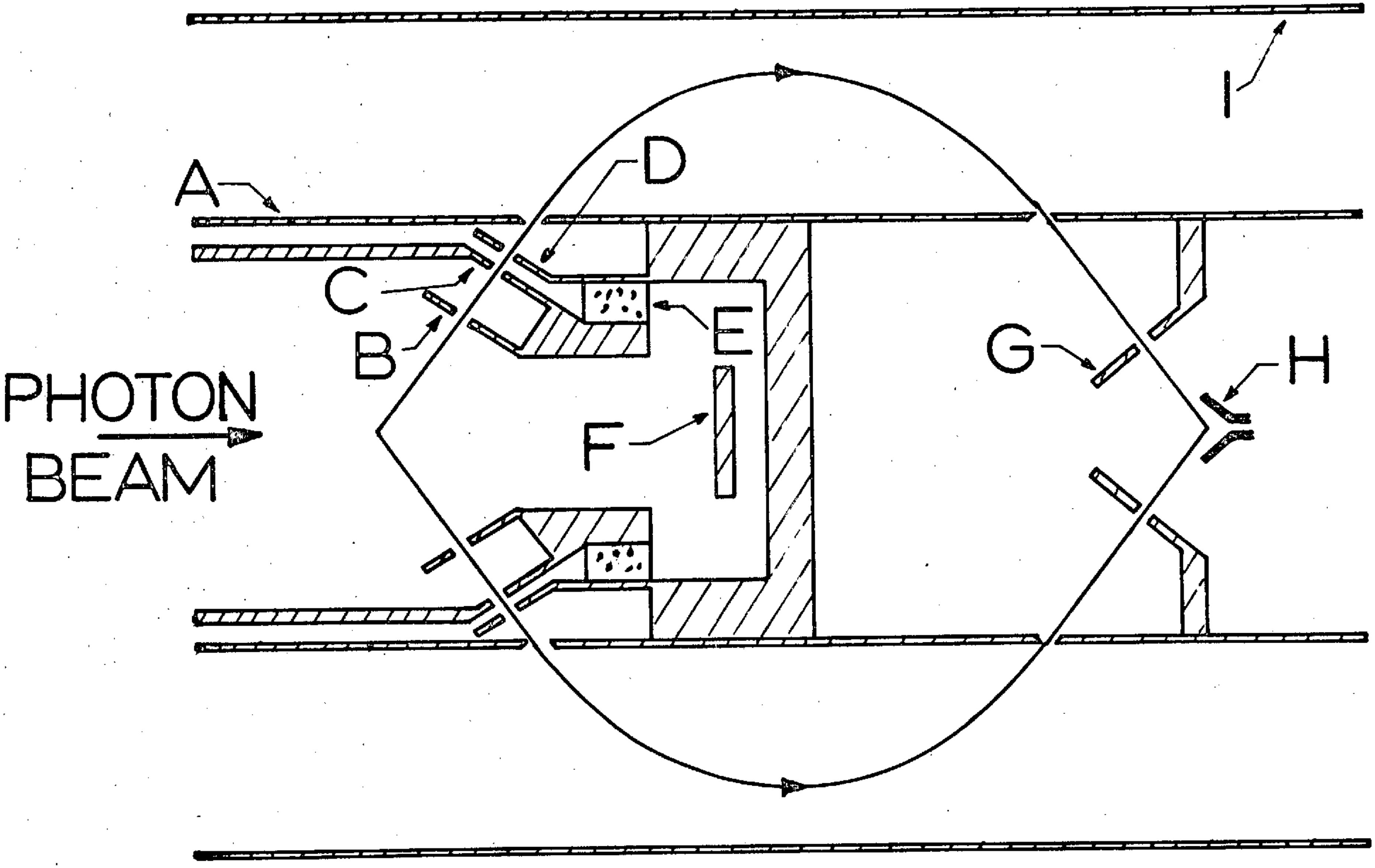
2. Collecting efficiency for a pass energy of 3 eV.

3. Collecting efficiency for the pass energies indicated, relative to that for a pass energy of 3 eV.

4. Collecting efficiency for zero retardation in the lens; spectra are recorded by scanning the voltage across the cylinders.

5. Count rate of Xe $^2P_{3/2}$ electrons at 584 Å. The dashed curve represents an $E^{1/2}$ dependence.

6. Comparison of the collecting efficiency obtained by the two methods. —— cross section method; - - - inverted pass curve method; ● normalization point.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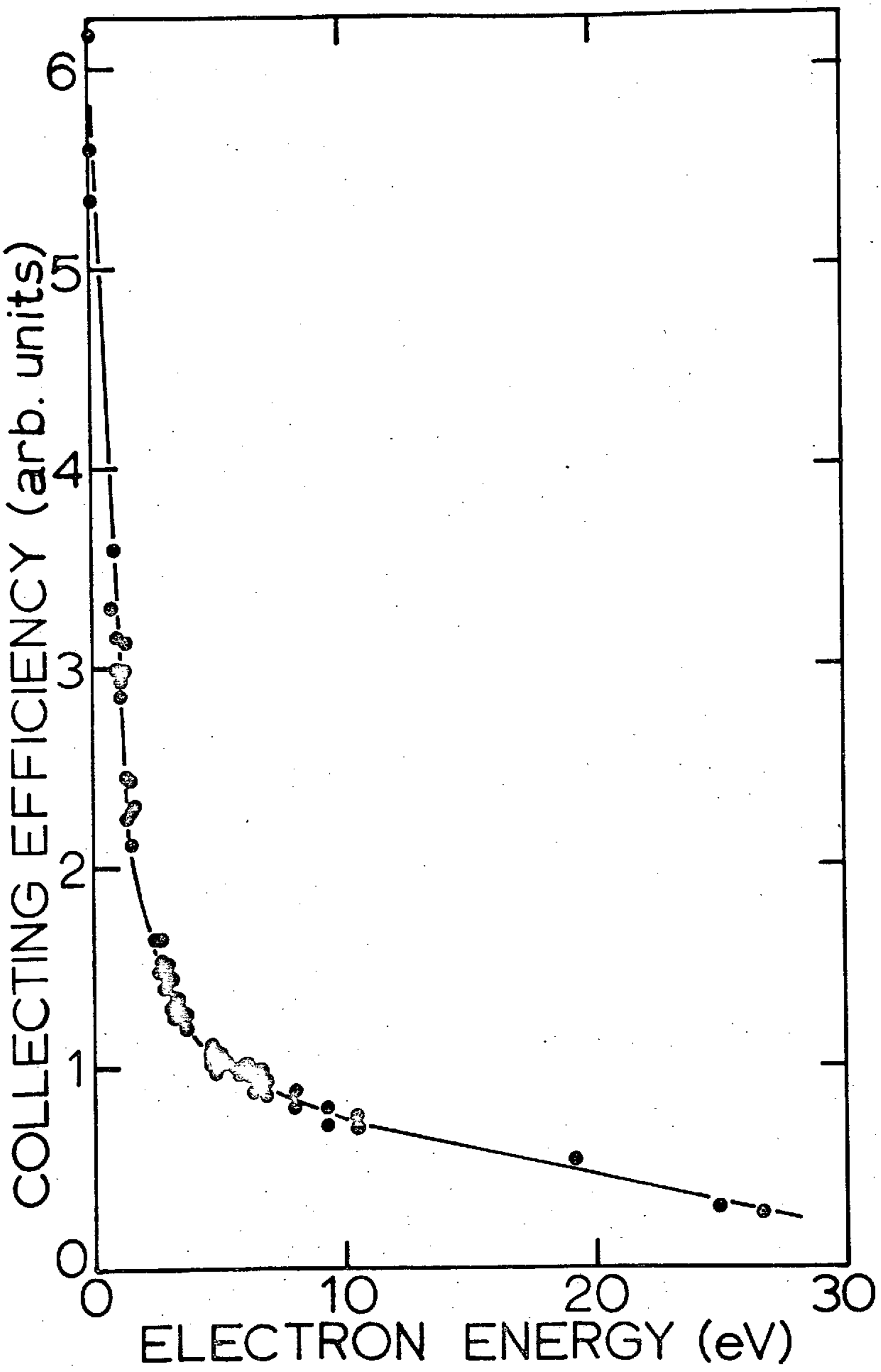
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2
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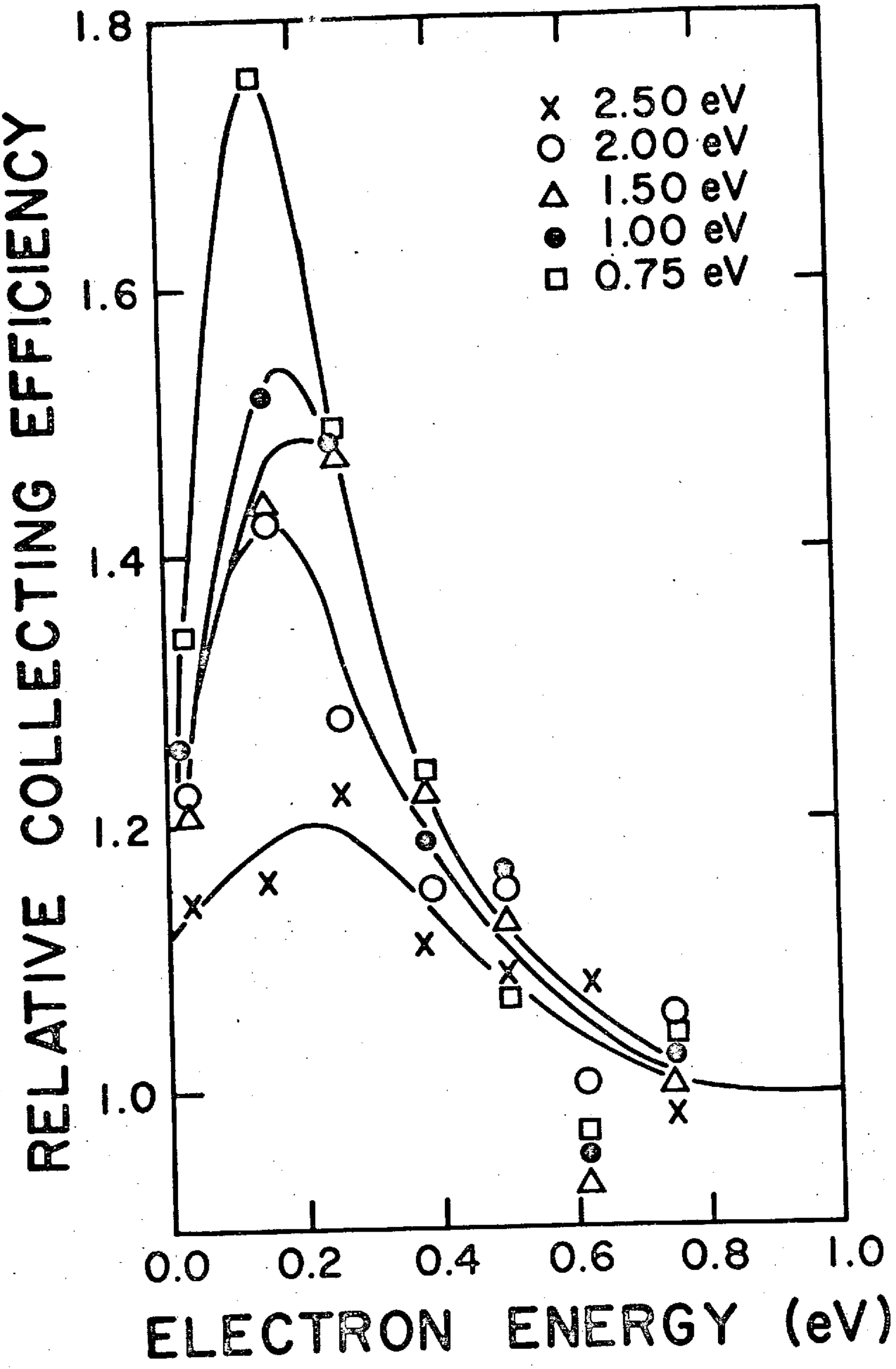
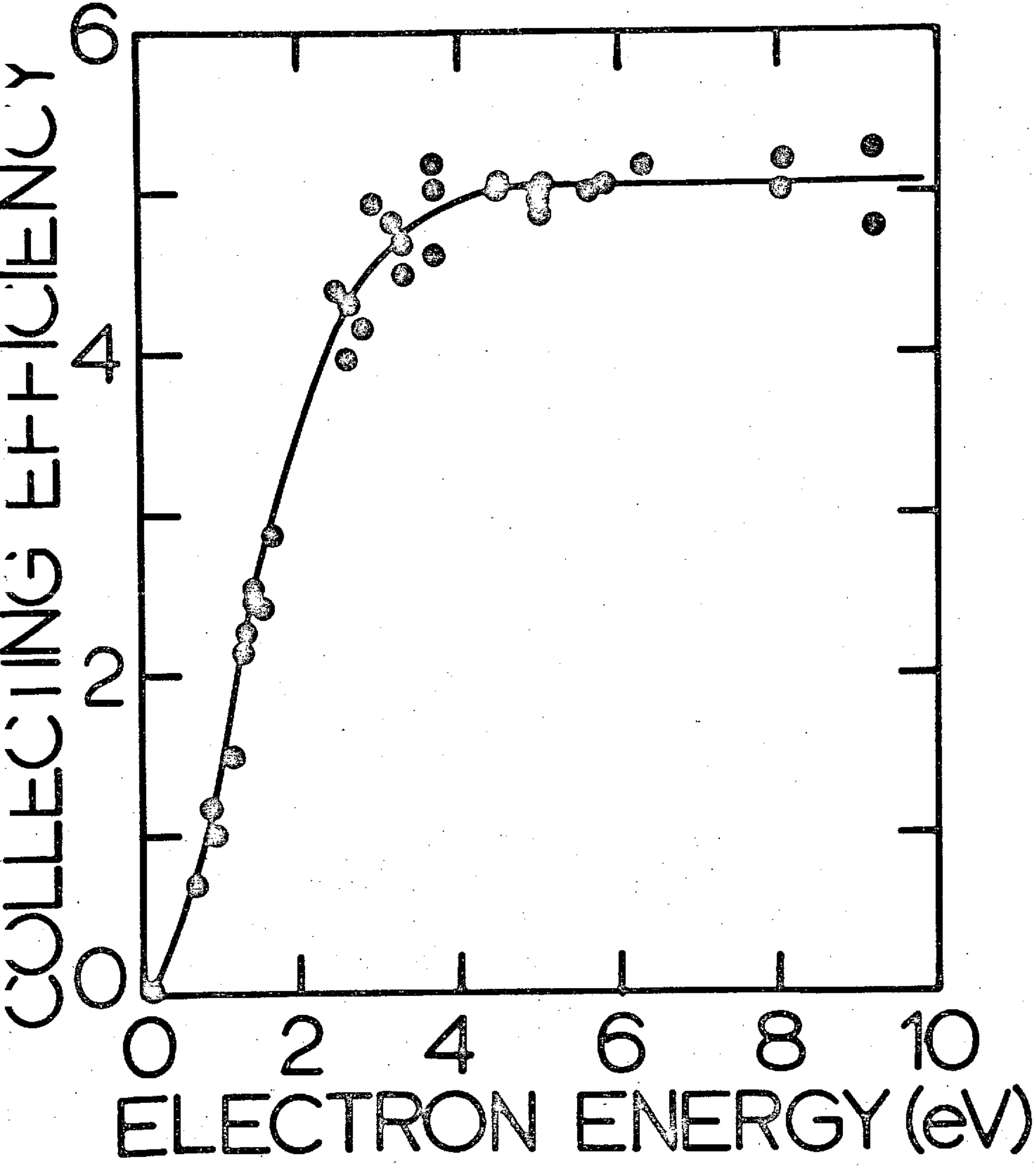
4
5
6
0
10
20
30
ELECTRON ENERGY (eV)


x 2.50 eV
○ 2.00 eV
△ 1.50 eV
● 1.00 eV
□ 0.75 eV
RELATIVE COLLECTING EFFICIENCY
1.8
1.6
1.4
1.2
1.0
0.0
0.2
0.4
0.6
0.8
1.0
ELECTRON ENERGY (eV)


COLLECTING EFFICIENCY
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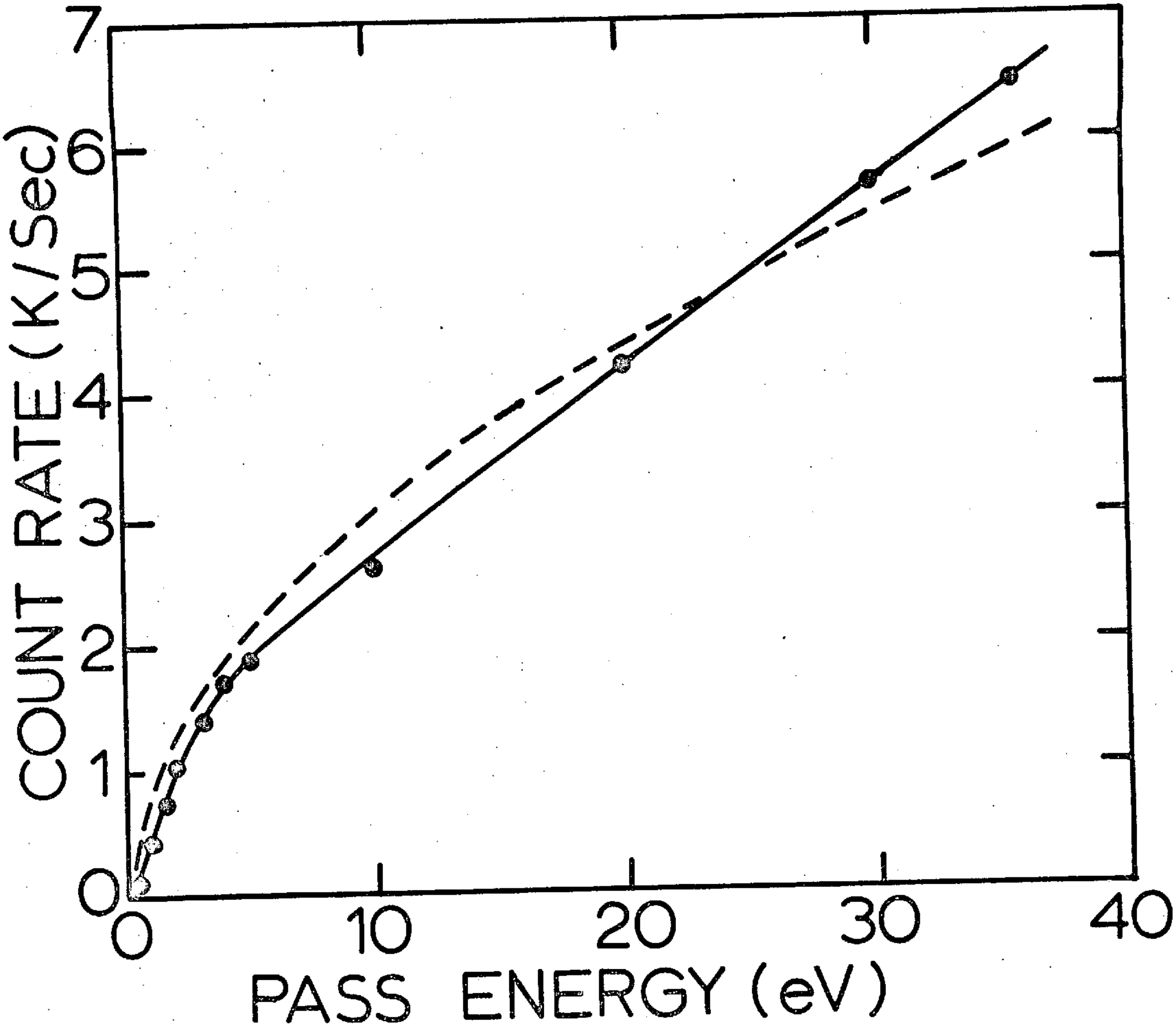
2
4
6
0
2
4
6
8
10
ELECTRON ENERGY (eV)


COUNT RATE (K/Sec)
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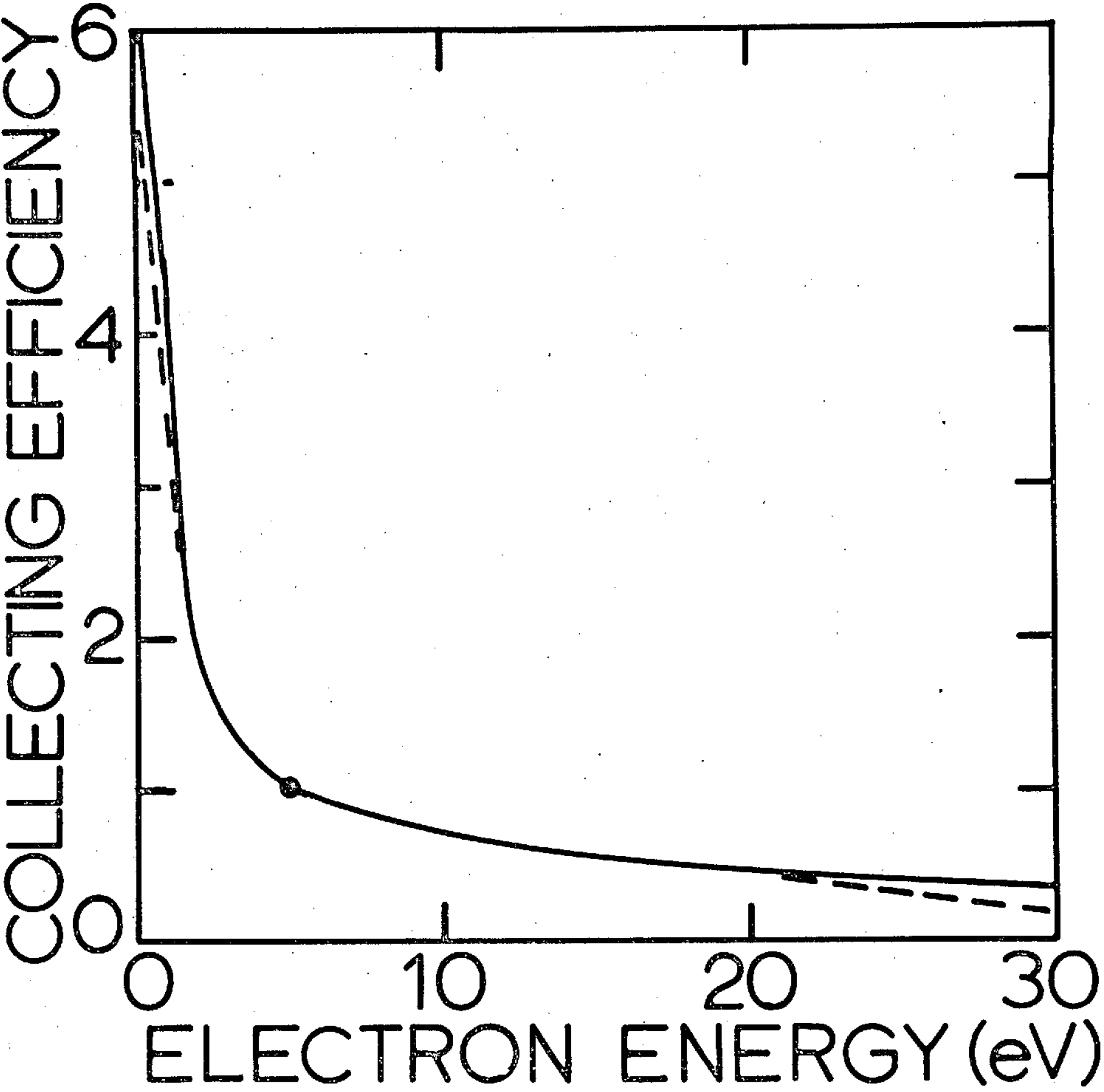
2
3
4
5
6
7
0
10
20
30
40
PASS ENERGY (eV)


COLLECTING EFFICIENCY
6
4
2
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20
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ELECTRON ENERGY (eV)