Secondary Electron Emission in the Limit of Low Energy and its Effect on High Energy Physics Accelerators

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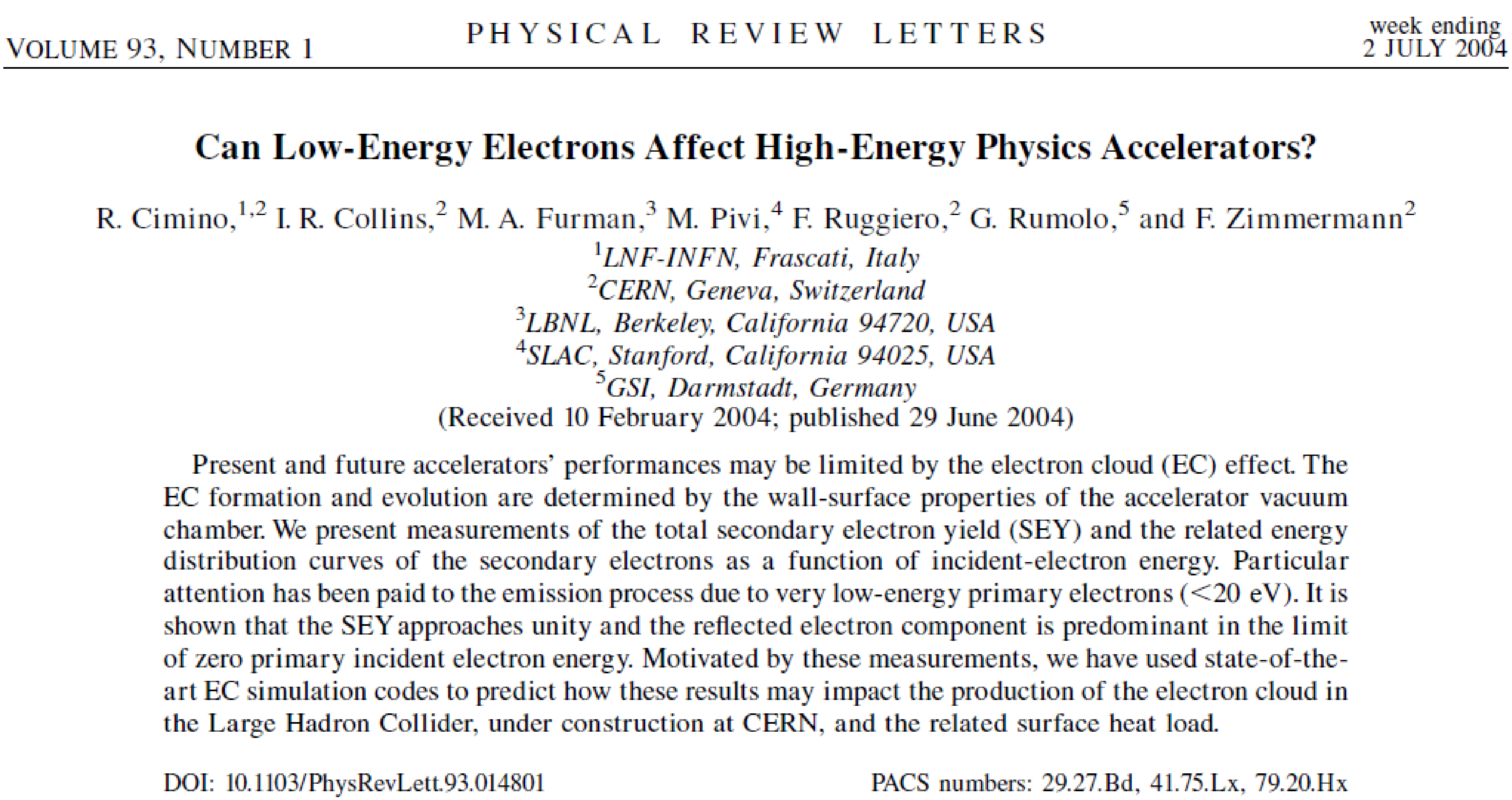
Is the secondary electron emission coefficient approaches unity in the limit of zero primary electron energy?



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Can Low-Energy Electrons Affect High-Energy Physics Accelerators?

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Present and future accelerators' performances may be limited by the electron cloud (EC) effect. The EC formation and evolution are determined by the wall-surface properties of the accelerator vacuum chamber. We present measurements of the total secondary electron yield (SEY) and the related energy distribution curves of the secondary electrons as a function of incident-electron energy. Particular attention has been paid to the emission process due to very low-energy primary electrons (<20 eV). It is shown that the SEY approaches unity and the reflected electron component is predominant in the limit of zero primary incident electron energy. Motivated by these measurements, we have used state-of-the-art EC simulation codes to predict how these results may impact the production of the electron cloud in the Large Hadron Collider, under construction at CERN, and the related surface heat load.

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Implications of the secondary electron emission coefficient approaching unity in the limit of zero primary electron energy

Total secondary electron emission coefficient (δ) and contribution to it of secondaries and reflected electrons from a fully scrubbed Cu surface at 9 K as a function of primary electron energy.

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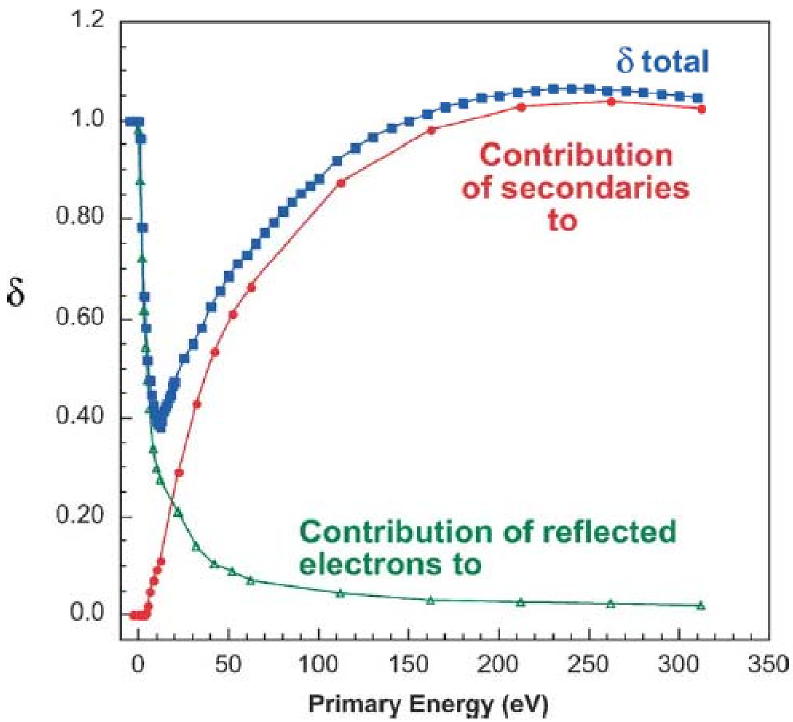
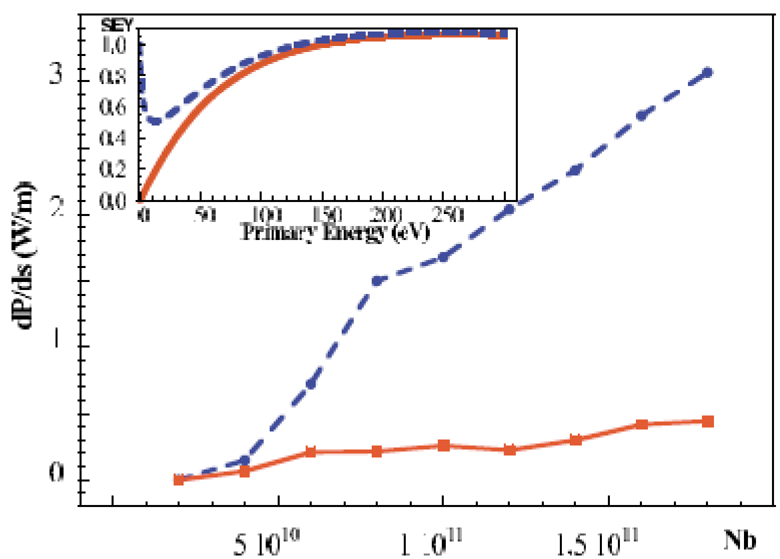


Simulated average heat load in an LHC dipole magnet as a function of proton bunch population at 0.45 TeV, for a SEY *considering the elastic reflection (dashed line)* or ignoring it (full line).

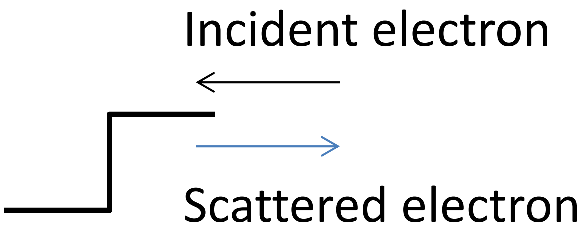


Long (forgotten) history of secondary electron emission studies suggests otherwise.

- Theoretical
  - Quantum diffraction from potential barrier

- Experimental
  - Difficulties of measurements at low incident electron energy
  - Previous careful measurements showing contrary observation
  - Probe measurements in plasma will not work

Quantum diffraction from potential barrier



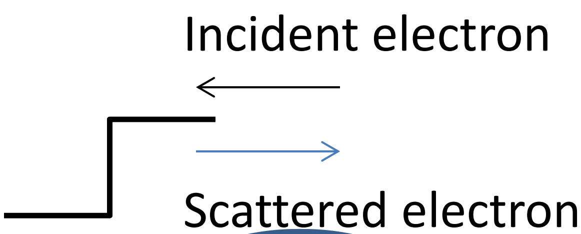
$$R = \left[\frac{(\varepsilon + V_i)^{1/2} - \varepsilon^{1/2}}{(\varepsilon + V_i)^{1/2} + \varepsilon^{1/2}} \right]^2$$

Quantum-mechanical effect due to electron diffraction off a simple negative potential step at the surface. The electron reflection coefficient, R, which is the ratio of the electron reflected and incident fluxes, for an electron with energy, ε, from a simple negative potential step (well) of amplitude V_i :

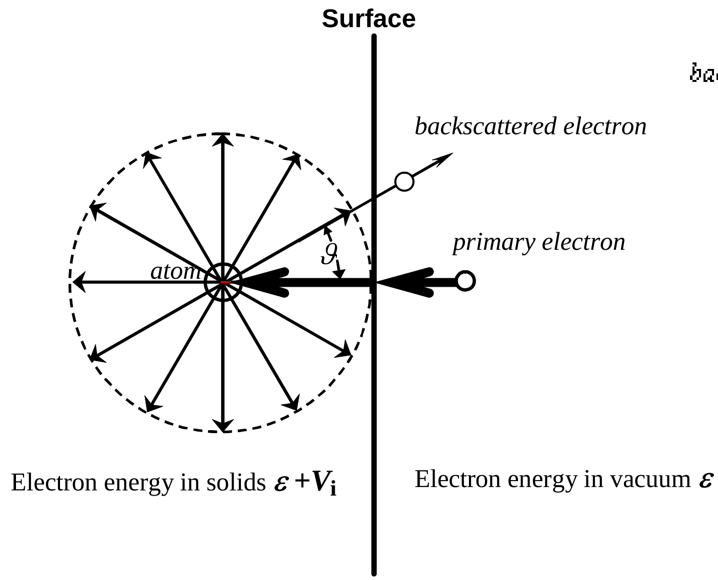
Here, V_i is the internal potential of solid, typically of 10-20 V, not 150V as mentioned in the Letter. Eq. gives R=0.67 for ε=0.01V_i, and R=0.29 for ε=0.1V_i. However, relation for the reflection coefficient does not account for electron acceleration toward the surface by the image charge in the metal. Due to image charge, an electron with negligible initial energy approaches the surface with energy of the order internal potential of solid. Detail calculation taking the image charge force into account [1] gives R=2-4%, for typical values of the internal potential of solid 10 eV.

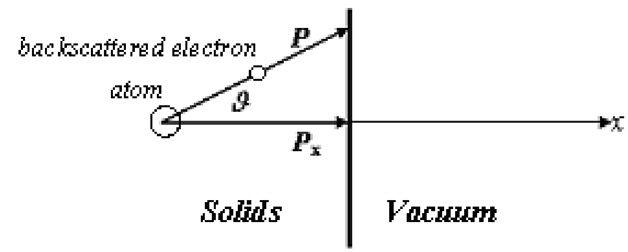
[1]. L. A. MacColl, Phys. Rev. 56, 699 (1939).

Quantum diffraction from potential barrier



$$R = \cancel{\left[\frac{(\varepsilon + V_i)^{1/2} - \varepsilon^{1/2}}{(\varepsilon + V_i)^{1/2} + \varepsilon^{1/2}}\right]^2}$$





$$\cos \vartheta_{max} = \sqrt{\frac{V_i}{\varepsilon + V_i}}$$

Due to image charge, an electron with negligible initial energy approaches the surface with energy of the order internal potential of solid. Electrons are scatter in collisions with atoms and cannot overcome barrier due to smaller normal to the surface velocity. Therefore, the escape angle and, as a result, escape probability and *R* go to zero when ε -> 0*.

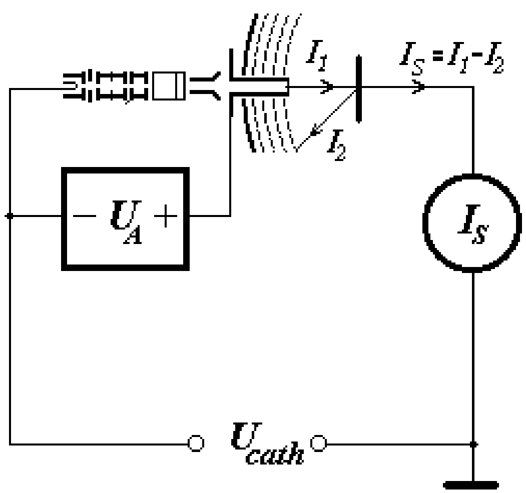
*I. M Bronshtein, B. S Fraiman. Secondary Electron Emission. Moscow, Russia: Atomizdat, p. 408 (1969).

It is very difficult to produce collimated electron beam with few eV energy for measurements of secondary electron emission coefficient at low incident electron energy.

An electron gun is at fixed energy.

Electrons are decelerated with a retarding potential at the target. =>

The energy spectrum of electrons arriving at the target is not known sufficiently, and many of returning electrons are reflected from a retarding electric field without any interaction with the target.



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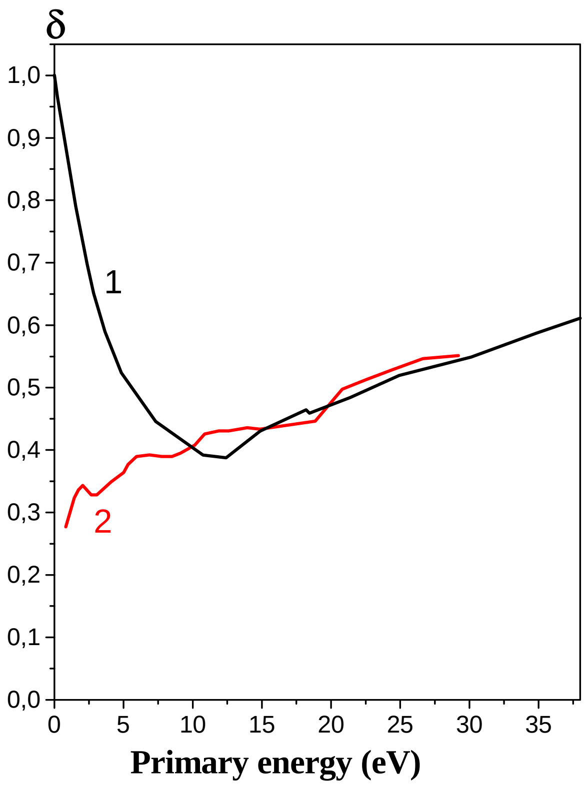
machine. To measure low-energy impinging primary electrons, a negative bias voltage was applied on the sample. Such a bias allows one to work at very low primary energy (close to 0 eV) while keeping the gun in a region where it is stable and focused, as measured by a line profile on a 1 mm slot Faraday cup. The

Previous careful measurements showing contrary observation

Total secondary electron yield of Cu as a function of incident electron energy. 1. from the letter for fully scrubbed Cu (*T*=10 K). 2. Experimental data for bulk Cu after heating in vacuum (room temperature).



1. R. Cimino, et al, Phys. Rev. Lett. **93**, 014801 (2004).
2. I. M Bronshtein, B. S Fraiman. Secondary Electron Emission. Moscow, Russia: Atomizdat, p. 408 (1969).

Other measurements reported the reflection coefficient of about 7% for incident electron energy below few electron volts for most pure metals.

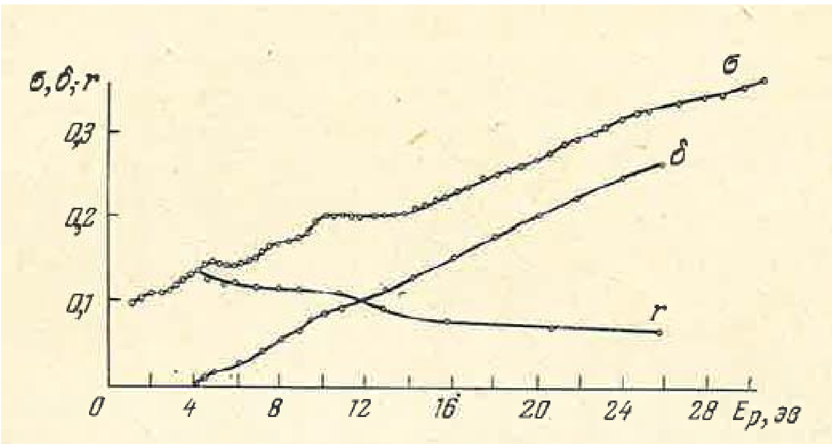
I.H. Khan, J. P. Hobson, and R.A. Armstrong, Phys. Rev. 129, 1513 (1963).

H. Heil, Phys. Rev. **164**, 887, (1967).

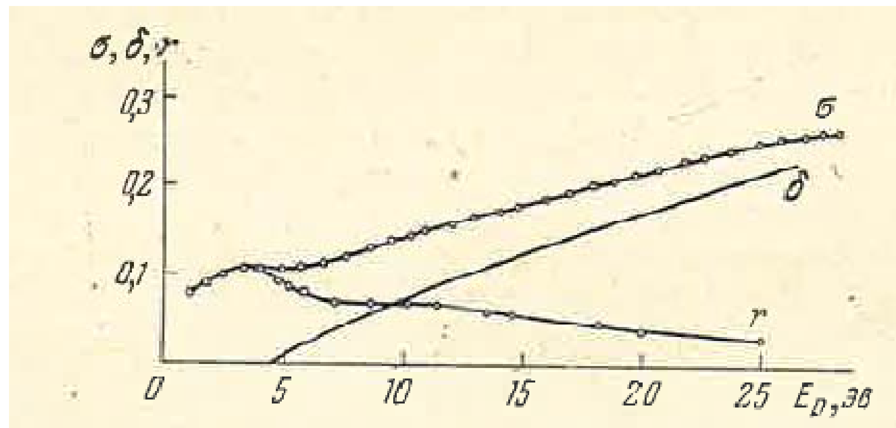
Z. Yakubova and N. A. Gorbatyi, Russian Physics Journal, 13 1477 (1970).

Previous careful measurements showing contrary observation

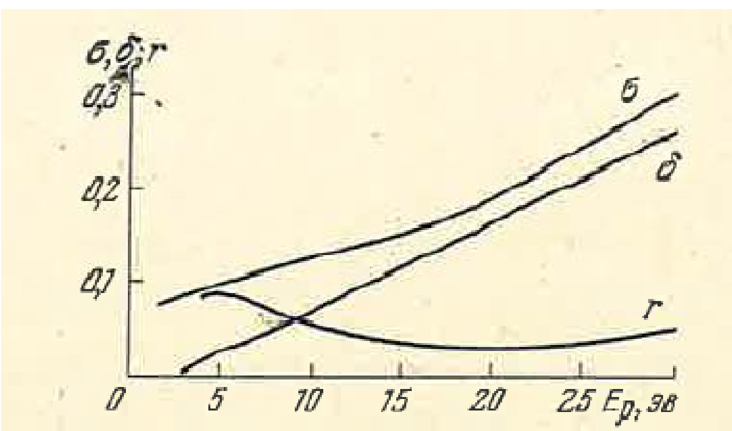
Total secondary electron yield of Al as a function of incident electron energy.



Total secondary electron yield of Ni.



Total secondary electron yield of Si.



I. M Bronshtein, B. S Fraiman. Secondary Electron Emission. Moscow, Russia: Atomizdat, p. 60 (1969).

Previous careful measurements showing contrary observation

Total secondary electron yield of Mo as a function of incident electron energy after degassing by prolong heating of target.

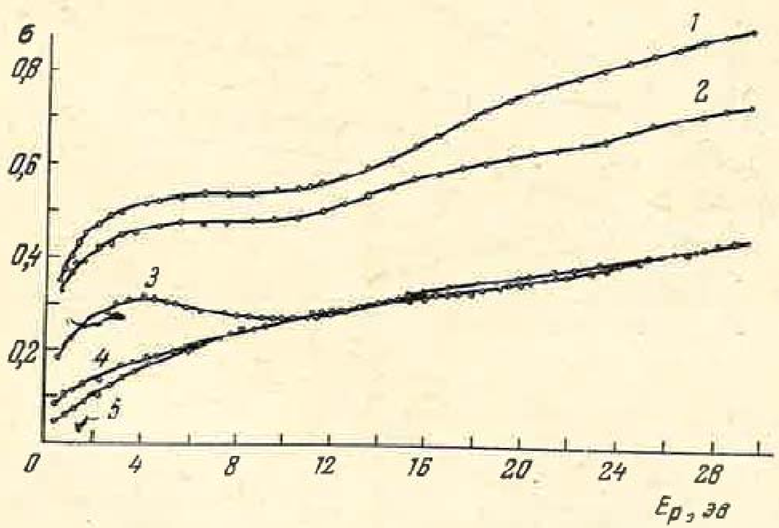


Рис. 2.9. Вторично-эмиссионные характеристики молибдена [596]. 1 — мишень не обезгажена; 2 — мишень калилась 1 *мин* при $t = 1000°$ С; 3—30 *мин* при $t \sim 1800°$ С; 4—4 *час* при $t \sim 2000°$ С; 5—8 *час* при $t \sim 2300°$ С;

Total secondary electron yield of Ge.

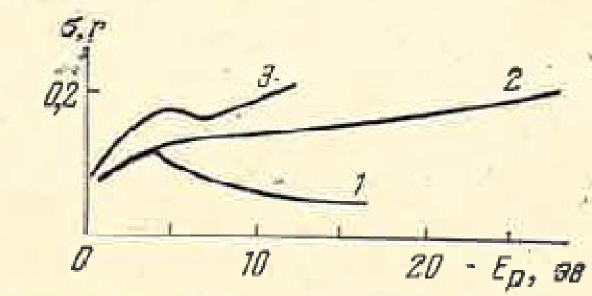


Рис. 2.8. Зависимости $r(E_p)$ (1) и $\sigma(E_p)$ (2) для напыленного слоя германия [704] и $\sigma(E_p)$ (3) для грани (100) монокристалла германия [634].

I. M Bronshtein, B. S Fraiman. Secondary Electron Emission. Moscow, Russia: Atomizdat, p. 60 (1969).

Previous careful measurements showing contrary observation

Total secondary electron yield of silver and tantalum as a function of incident electron energy after degassing by prolong heating of target.

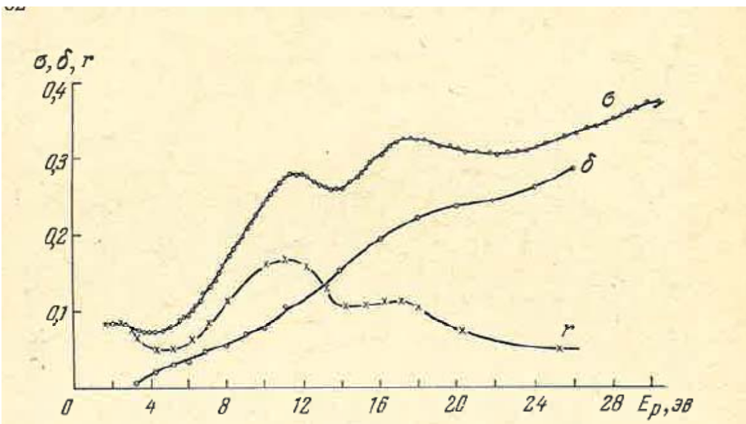
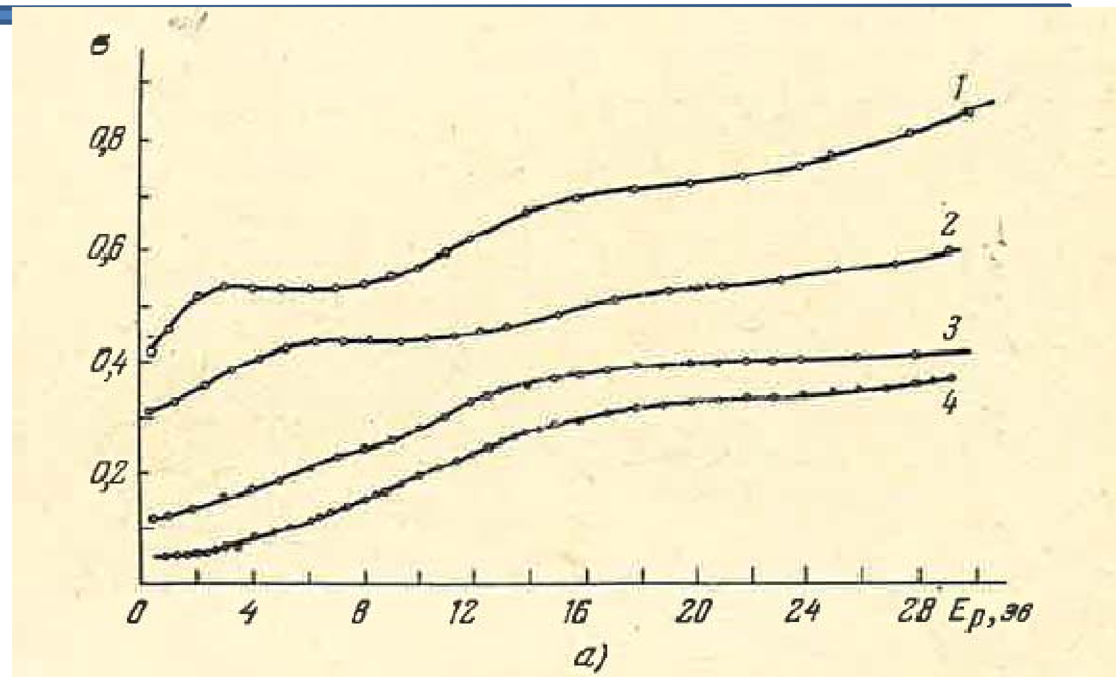


Рис. 2.10. Зависимости $\sigma(E_p)$, $\delta(E_p)$ и $r(E_p)$ для слоя серебра, напыленного в сверхвысоком вакууме [597].



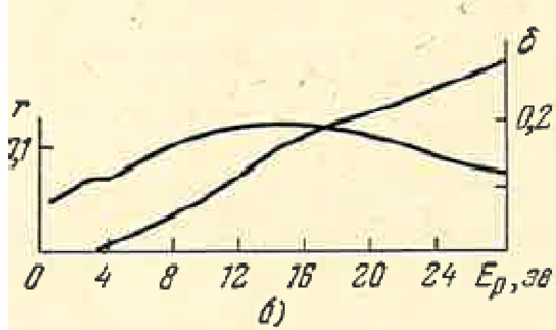


Рис. 2.11. Вторично-эмиссионные характеристики тантала [596].

а) Зависимости $\sigma(E_p)$: 1 — мишень не обезгажена; 2 — мишень калилась 2 часа при $t \backsim 1300°$ C; 3 — 5 мин при $t \backsim 2000°$ C; 4 — 10 час при $t \backsim 2300°$ C; б) зависимости $\delta(E_p)$ и $r(E_p)$.

Previous careful measurements showing contrary observation

Total secondary electron yield of tungsten and gold.

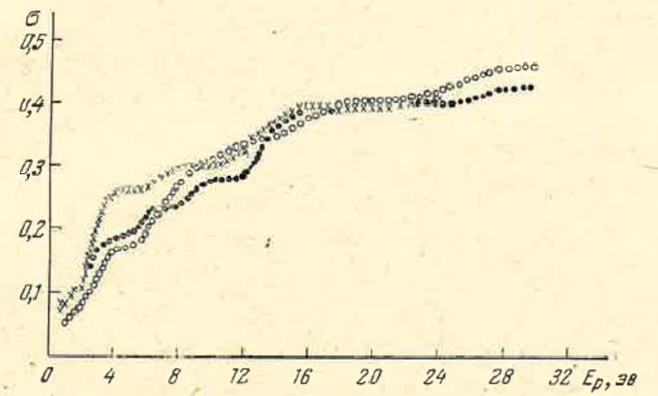


Рис. 2.12. Зависимости σ (E_p) для вольфрама [771].
× — грань (110); ● — грань (112); ⊙ — поликристаллическая лента.

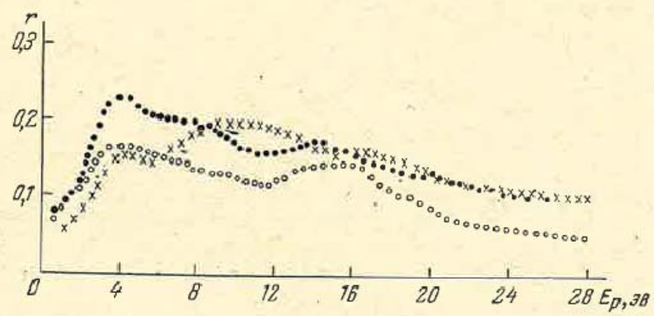


Рис. 2.13. Зависимости r (E_p) для вольфрама [771].
● — грань (110); ⊙ — грань (112); × — поликристаллическая лента.

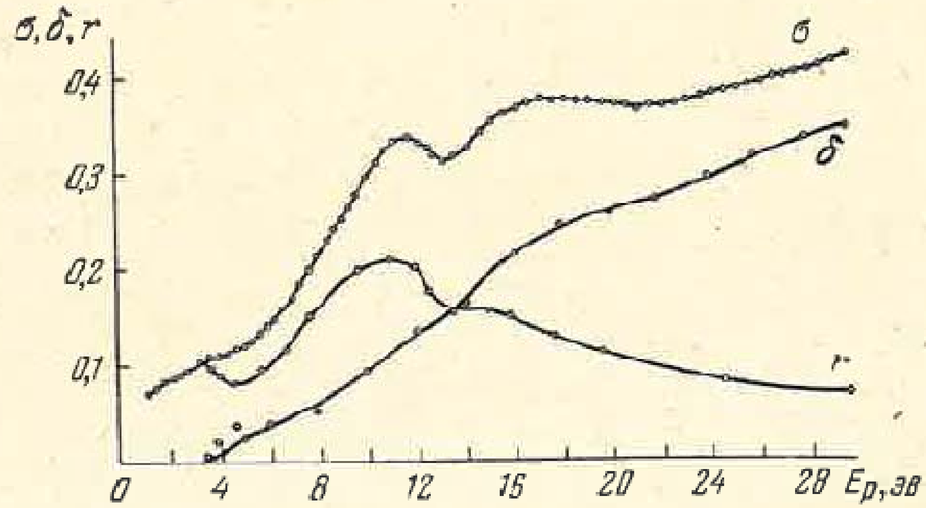


Рис. 2.15. Зависимости σ (E_p), r (E_p) и δ (E_p) для золота [597].

Reflection is large in dielectrics based on oxides or halogens. Maximum is ~0.7 at 3eV

Total secondary electron yield of NaCl, and oxides of barium and yttrium. Emission is increased due to scattering on dislocations, phonons and surface states. Emission starts from threshold of photo-effect as a function of photon

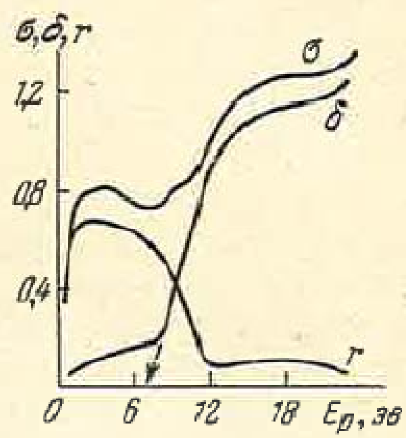


Рис. 2.17. Зависимости $\sigma(E_p)$, $\delta(E_p)$ и $r(E_p)$ для монокристалла NaCl [772].
Стрелкой отмечена энергия, соответствующая границе собственного оптического поглощения NaCl.

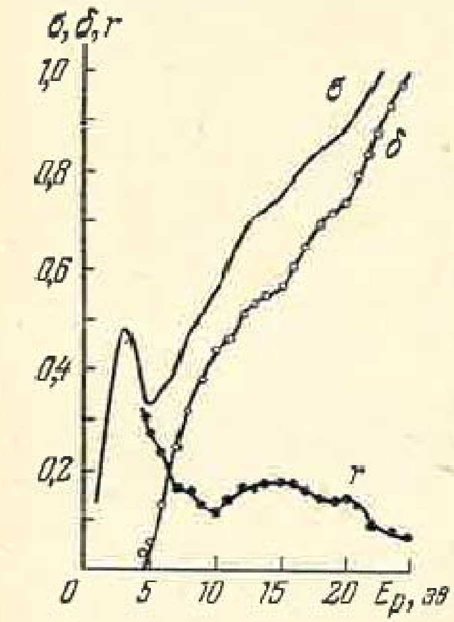


Рис. 2.22. Зависимости $\sigma(E_p)$, $\delta(E_p)$ и $r(E_p)$ для окиси бария [720].

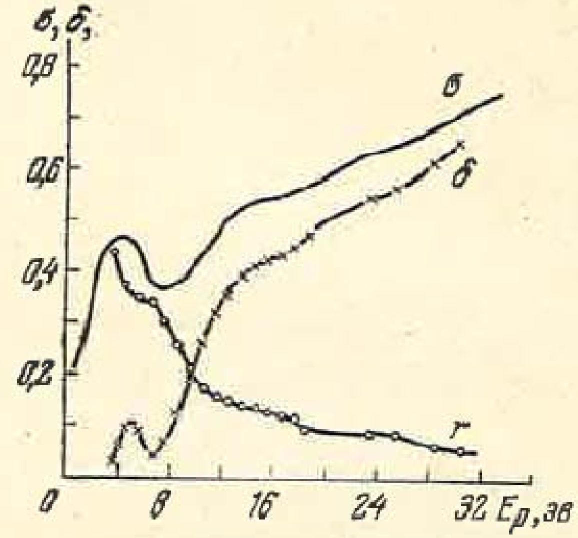


Рис. 2.23. Зависимости $\sigma(E_p)$, $\delta(E_p)$ и $r(E_p)$ для окиси иттрия [720].

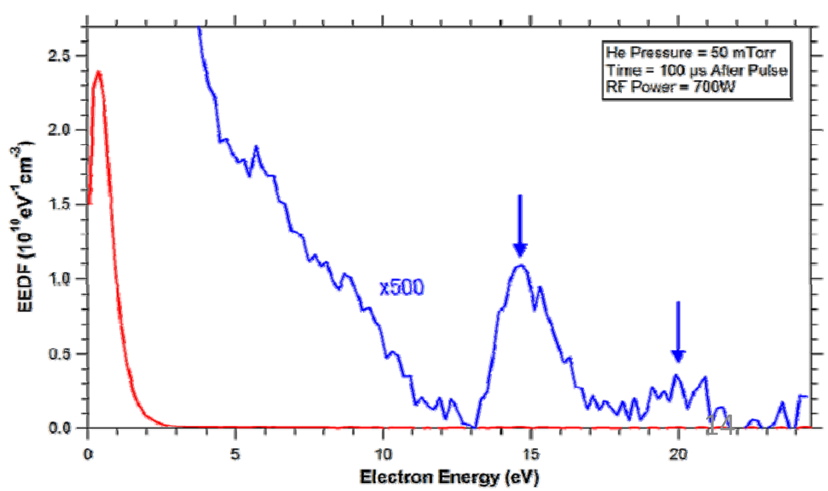
If the reflection coefficient of low energy electrons is large, the operation of probes collecting electron current will be strongly affected[1]

This has not been observed. In the afterglow, electrons cool rapidly to T_e ~ 0.2 eV. A small amount of fast electrons with well defined energy arise from the Penning ionization

$A^* + A^* \rightarrow A + A^+ + e_f$[2].

By measuring probe characteristic it is possible to determine if the peak on probe characteristic is widen or shifted relative to the value due to electron reflection form the probe surface. It was shown that there is no change in probe characteristics for clean probe within accuracy 0.16eV [2].

1. K. Wiesemann, Ann. Phys. *Lpz* **27** 303 (1971).
2. V. I. Demidov, N. B. Kolokolov, and O. G. Toronov, Sov. Phys. Tech. Phys. **29**, 230 (1984).



Conclusions

New discovery is sometimes old forgotten facts.