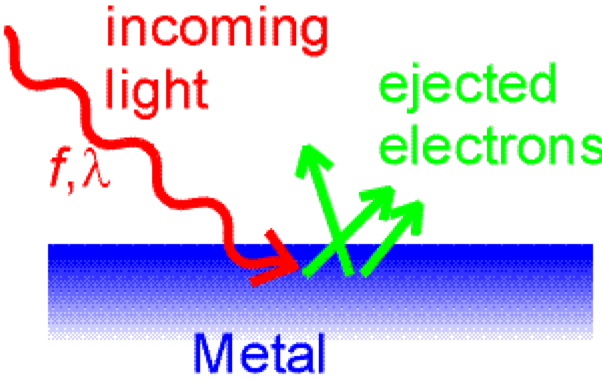
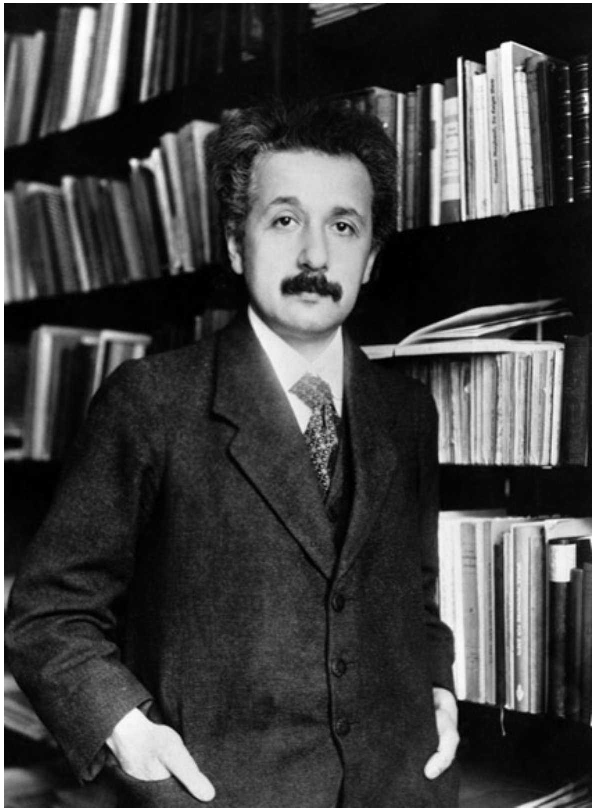
Photoelectric effect and X-rays

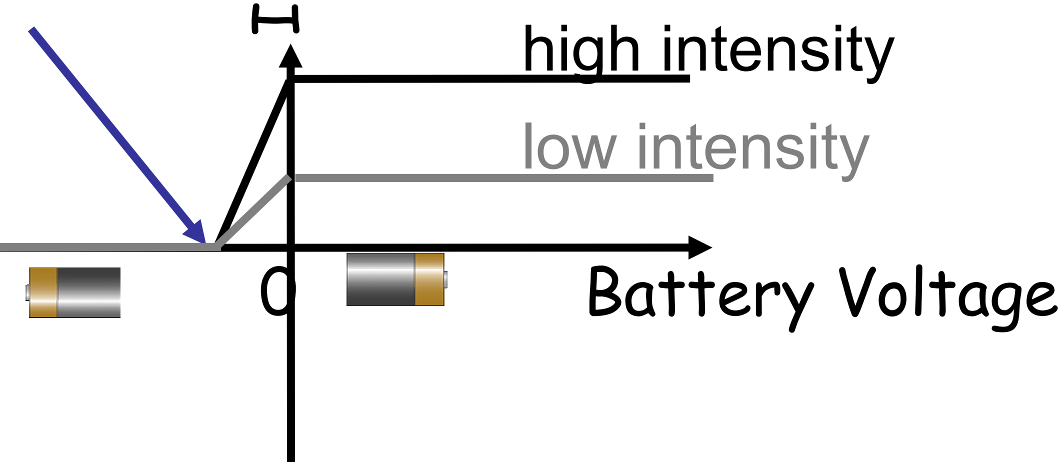
Announcements:

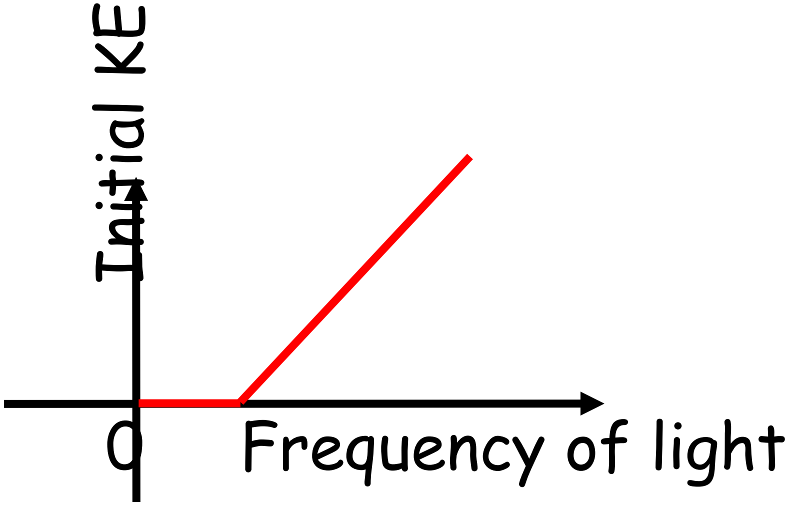
- First midterm is 7:30pm on 2/17/09 in this room.
- Formula sheet has been posted
- Old exams are on CULearn
- Next weeks homework has been posted and is due Wednesday as usual. It covers material that will be on the test so you should do it before Tuesday night.





Putting what we learned together





How does stopping potential (voltage) relate to KE (of electrons)?

To overcome a voltage V, the electron must have an initial KE of eV.

With an initial KE of eV, it would end up at the other side of the potential V with KE of 0.

What effect does the type of metal have?

Summary of photoelectric effect results

http://phet.colorado.edu

1. The current is linearly proportional to the light intensity.
2. Current appears with no delay.
3. Electrons only emitted if frequency of light exceeds a threshold. (same as "if wavelength short enough").
4. Maximum energy that electrons come off with increases linearly with frequency (=c/wavelength).
   (Max. energy = stopping potential)
5. Threshold frequency depends on type of metal.

How do these compare with classical wave predictions?

Classical wave predictions versus experimental results

•Increasing intensity will increase the current.
experiment matches

•Current vs voltage step at zero then flat.
(flat part matches, but experiment has tail of energetic electrons, *energy of which depends on color*)

•Color light does not matter, only intensity.
experiment shows strong dependence on color

•Takes time to heat up ⇒ current low and increases with time.
experiment: electrons come out immediately, no time delay to heat up and no increase in current with time.

Summary of what we know so far

1. If light can kick out electron, then even the tiniest intensities will do so. Electron kinetic energy does **not** depend on intensity.
   (Light energy must be getting concentrated/focused somehow)

2. Electron initial kinetic energy increases linearly with frequency.
   (This concentrated energy is linearly related to frequency)

3. There exists a minimum frequency below which light won't kick out electrons.
   (Need a certain amount of energy to free electron from metal)

(Einstein) Need "photon" picture of light to explain observations:
- Light comes in chunks ("particle-like") of energy ("photon").
- A photon interacts with a single electron.
- Photon energy depends on frequency of light; low frequency photons don't have enough energy to free an electron.

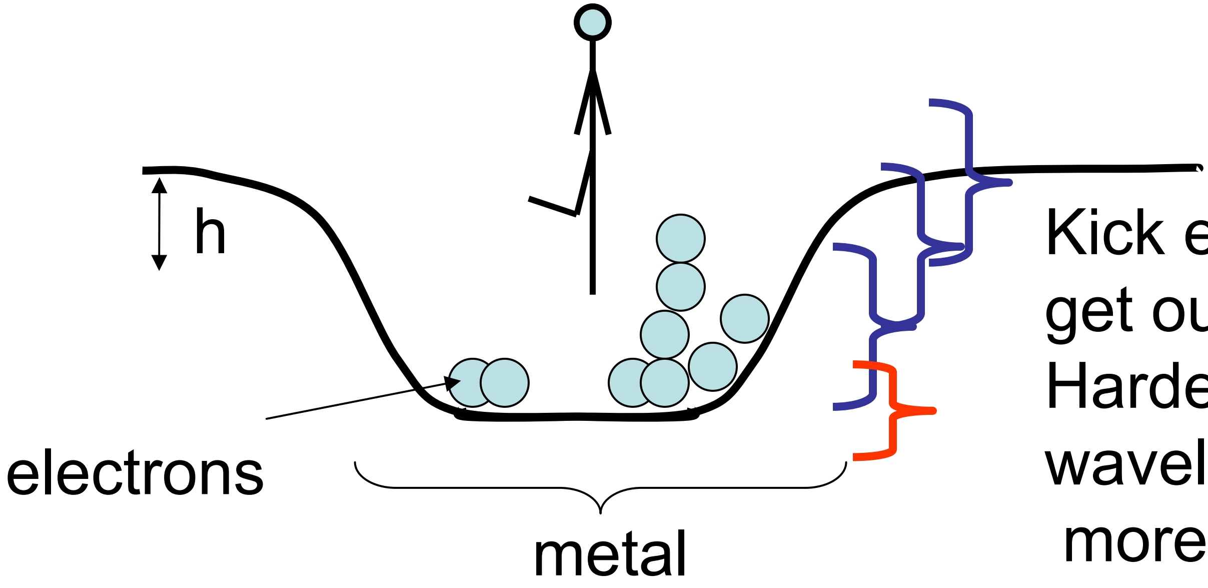
Analogous to a kicker in a pit

Light is like a kicker…
Puts in energy. All concentrated on one ball/electron.
Blue kicker always kicks the same,
and harder than red kicker always kicks.

Ball emerges with:

KE = kick energy - mgh

mgh = energy needed to make it up hill and out.
mgh for highest electron is analogous to work function.



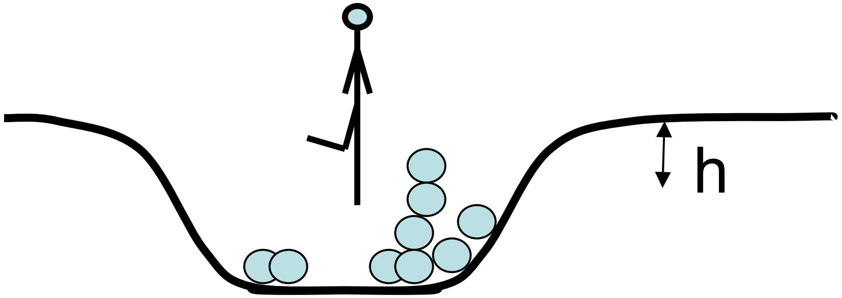
Kick energy. Top ones get out, bottom don't. Harder kick (shorter wavelength light), more get out.

Analogous to a kicker in a pit

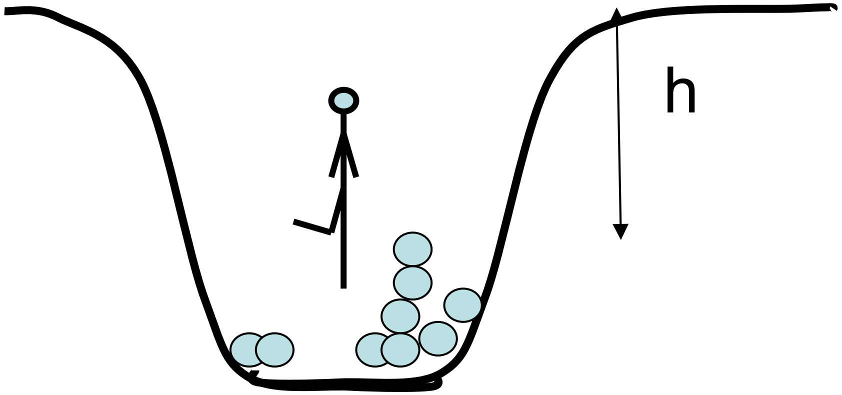
Light is like a kicker…
Puts in energy. All concentrated on one ball/electron.
Blue kicker always kicks the same, and harder than red kicker always kicks.

Ball emerges with:
KE = kick energy - mgh

energy needed to get most energetic (highest) electron out of pit ("work function")



sodium- easy to kick out
small work function ⇔ shallow pit

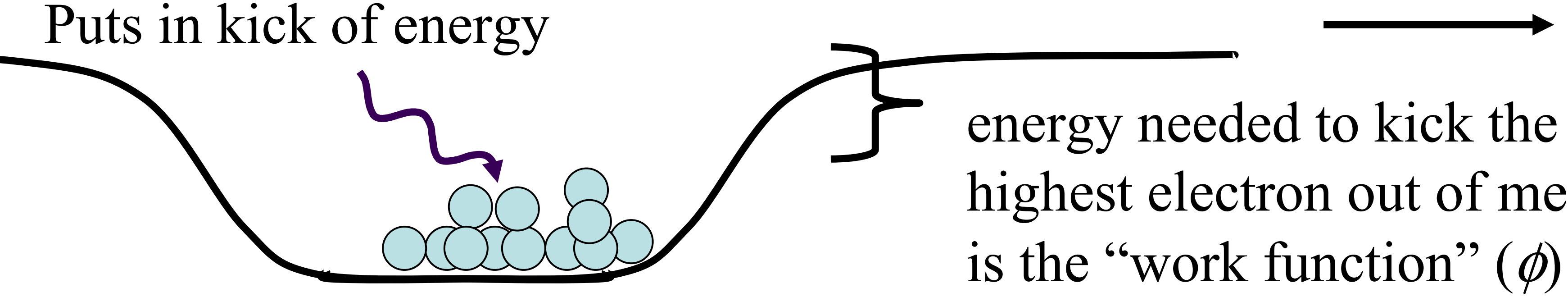


platinum, hard to kick out
large work function ⇔ deep pit

Einstein's Explanation of the Photoelectric Effect

KE = photon energy – work function

Photon…
Puts in kick of energy



energy needed to kick the highest electron out of metal is the "work function" (ϕ)

Each photon has: $E = hf$ = Planck's constant * Frequency

(Energy in Joules)	(Energy in eV)
$E = hf = 6.626 \times 10^{-34}$ J·s • f	$E = hf = 4.14 \times 10^{-15}$ eV·s • f
$E = hc/\lambda = 1.99 \times 10^{-25}$ J·m / λ	$E = hc/\lambda = 1240$ eV·nm / λ

$$KE_{\max} = hf - \phi$$

Depends on the type of metal.

Clicker question 1 — Set frequency to DA

A photon with a wavelength of 300 nm kicks out an electron with kinetic energy KE_{300}. A photon with half this wavelength hits the same electron in the same metal. This kinetic energy will be:

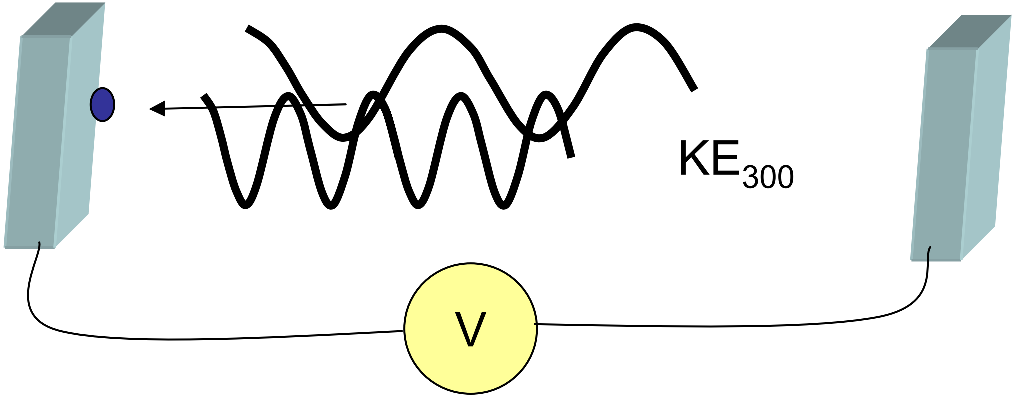
A) less than $\frac{1}{2}KE_{300}$

B) $\frac{1}{2}KE_{300}$

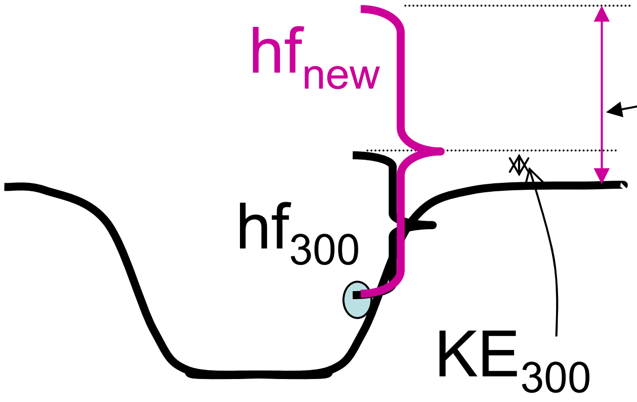
C) KE_{300}

D) $2KE_{300}$

[✓ E) more than $2KE_{300}$]



KE = photon energy − work function = $hf - \phi$



½ wavelength = 2 x frequency so $E_{\gamma,new} = 2hf_{300}$

$KE_{new} = 2hf_{300} - \phi$, compared with

$KE_{300} = hf_{300} - \phi$

KE_{new} is more than $2KE_{300}$

The simulation might prompt the following question:

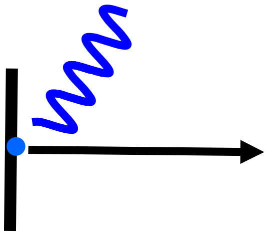
Why do the electrons in the simulation come out with different energies if all the incoming photons have the same energy?

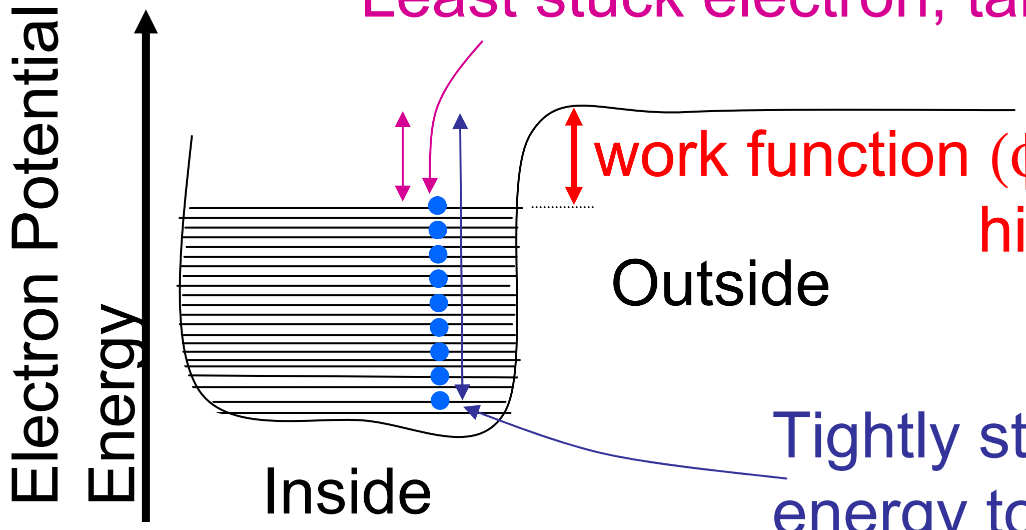
Conservation of energy *does* still work!

Energy in = Energy out

Photon energy = Work function + Initial KE of electron

(gets electron out) (left-over energy)





Least stuck electron, takes least energy to kick out

work function (ϕ) = energy needed to kick highest electron out of metal

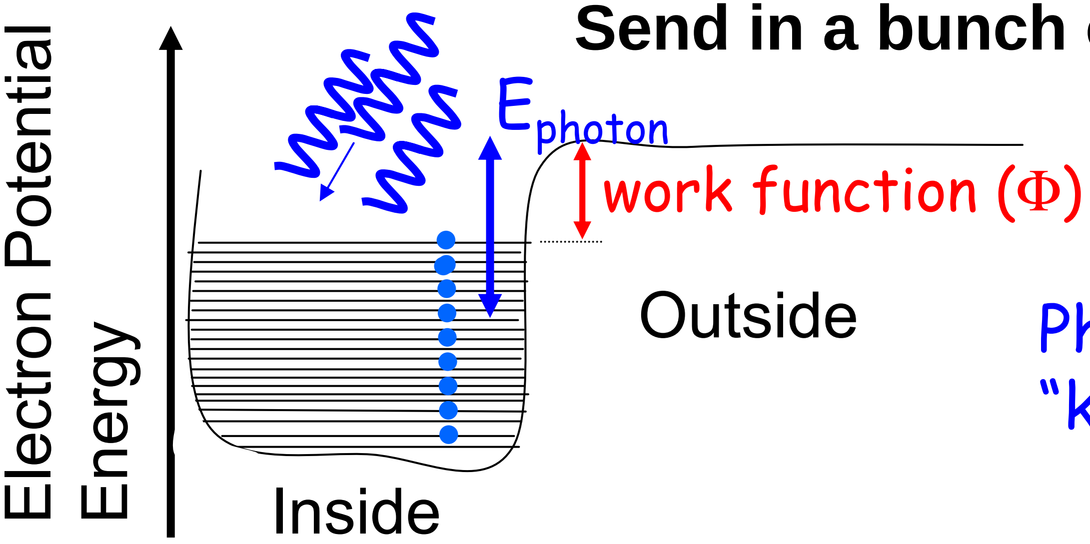
Tightly stuck, needs more energy to escape

Apply Conservation of Energy with Photons.

Energy in = Energy out

Photon energy = energy to get electron out + KE of liberated electron

Send in a bunch of blue photons…



Photon gives electron “kick of energy”.

Electrons have equal chance of absorbing photon:

→ KE_{max} = photon energy − ϕ (least bound electrons)

→ Min KE = 0 (electrons just barely released)

→ Too tightly bound to get free, energy goes into heat or light.

Will learn more about electron energy levels over next 2 months.

http://www.colorado.edu/physics/phys2170/

Typical energies for photoelectric problems

Photon Energies:

Each photon has: $E = hf$ = Planck's constant * Frequency

(Energy in Joules)

$E = hf = 6.626 \times 10^{-34}$ J·s • f

$E = hc/\lambda = 1.99 \times 10^{-25}$ J·m / λ

(Energy in eV)

$E = hf = 4.14 \times 10^{-15}$ eV·s • f

$E = hc/\lambda = 1240$ eV·nm / λ

Red Photon: 650 nm

$$E_\gamma = \frac{1240\,\mathrm{eV \cdot nm}}{650\,\mathrm{nm}} = 1.91\,\mathrm{eV}$$

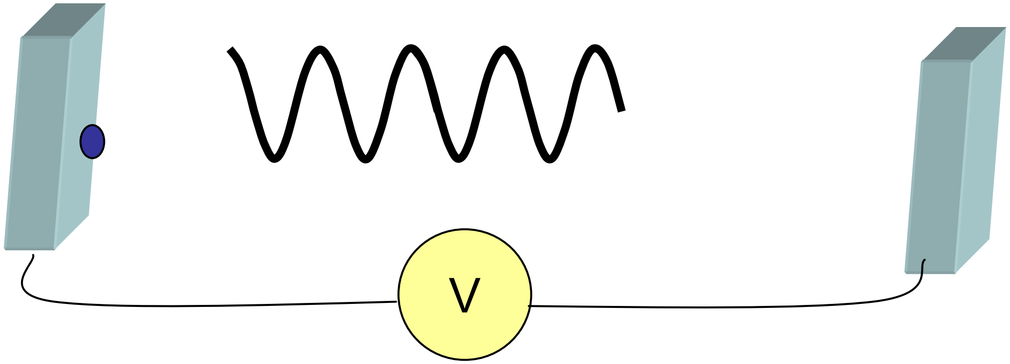
Work functions of some metals (in eV):

Aluminum	4.1 eV	Cesium	2.1	Lead	4.14	Potassium	2.3
Beryllium	5.0 eV	Cobalt	5.0	Magnesium	3.7	Platinum	6.3
Cadmium	4.1 eV	Copper	4.7	Mercury	4.5	Selenium	5.1
Calcium	2.9	Gold	5.1	Nickel	5.0	Silver	4.7
Carbon	4.81	Iron	4.5	Niobium	4.3	Sodium	2.3

Clicker question 2

Set frequency to DA

Light with wavelength of 300 nm ejects electrons from a metal. The voltage required to stop the electrons is 1.8 V. What is the work function of this metal?



A) 1.2 eV
B) 2.3 eV
C) 4.1 eV
D) 6.4 eV
E) 11.3 eV

$E = hf = 6.626 \times 10^{-34}\ \text{J·s} \cdot f = 4.14 \times 10^{-15}\ \text{eV·s} \cdot f$

$E = hc/\lambda = 1.99 \times 10^{-25}\ \text{J·m} / \lambda = 1240\ \text{eV·nm} / \lambda$

The photoelectric effect formula is a consequence of conservation of energy: E_γ = electron energy + energy to escape metal.

Can also write this as $KE_{max} = E_\gamma - \phi$.

Here $E_\gamma = hf = hc/\lambda = 1240\ \text{eV·nm} / 300\ \text{nm} = 4.1\ \text{eV}$

So $\phi = E_\gamma - KE_{max} = 4.1\ \text{eV} - 1.8\ \text{eV} = 2.3\ \text{eV}$