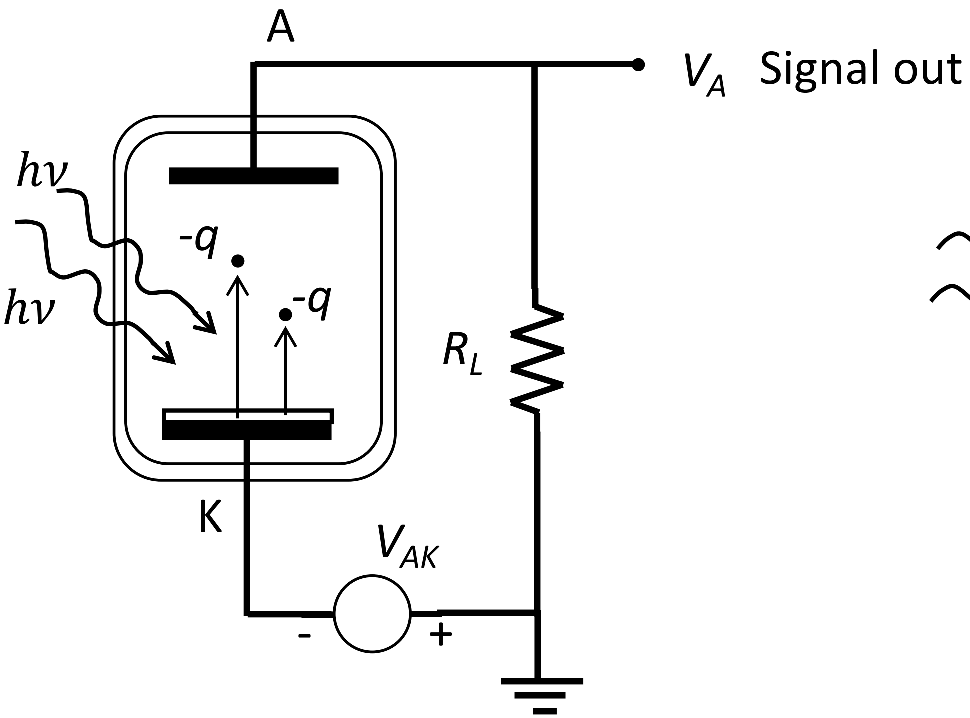
COURSE OUTLINE

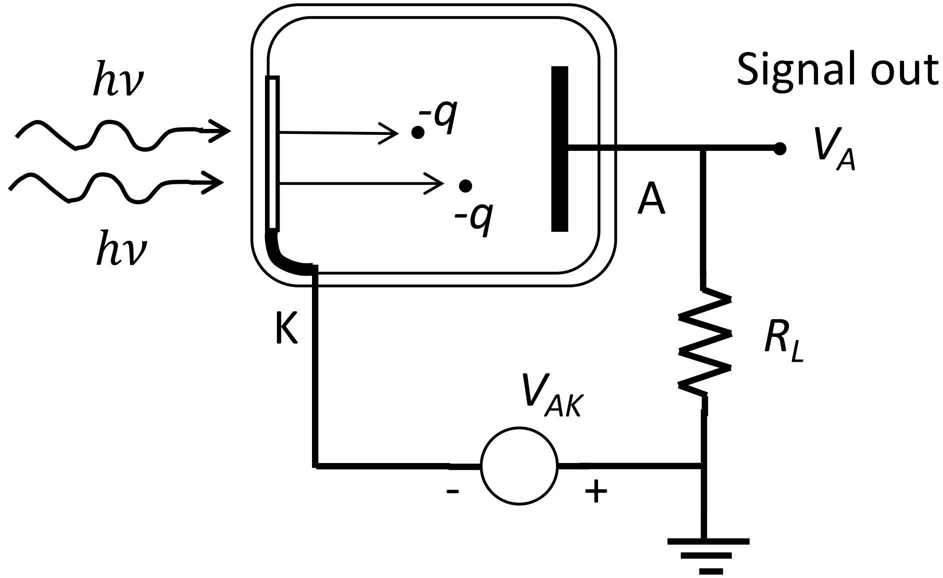
- Introduction
- Signals and Noise
- Filtering
- Sensors: PD2 - PhotoTubes

Vacuum Tube Photo-Diodes or Photo-Tubes

- PhotoTube (PT) device structure
- PT current-voltage characteristics and stationary equivalent circuit
- PT dynamic response and dynamic equivalent circuit
- Photo-emission of electrons, photocathode technology and Photocathode types
- Detector Dark Current and Noise
- Photocathode Noise-Equivalent-Power NEP and Detectivity

PhotoTube device structures





SIDE-WINDOW TUBE

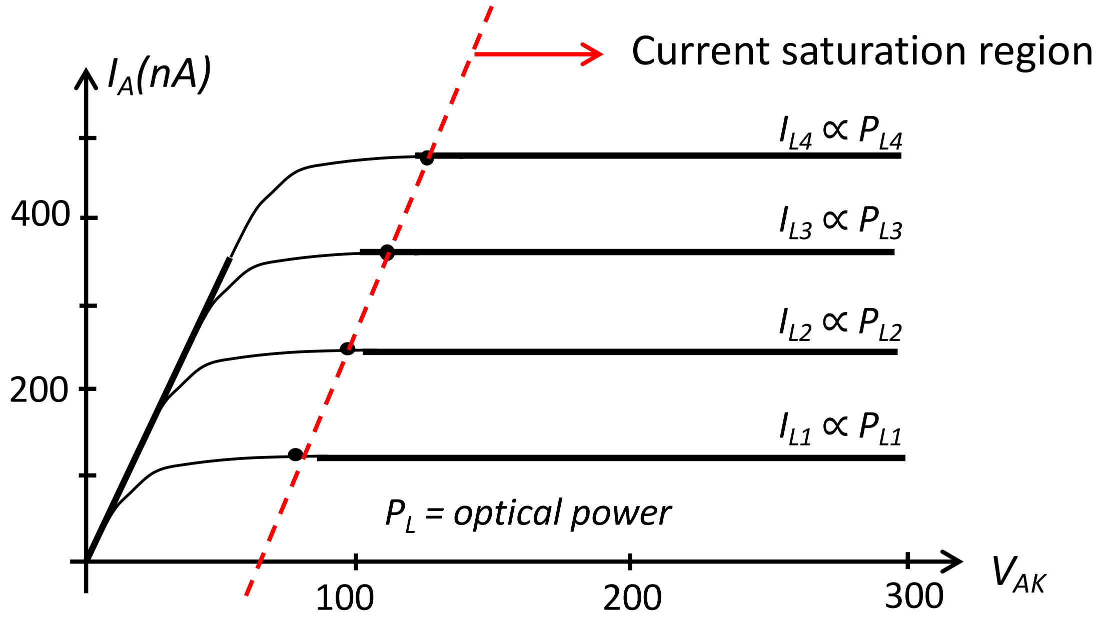
- Photocathode: thick opaque layer deposited on metal support electrode
- Side window of the glass tube: unfavourable geometry, collection of light on the photocathode is uneasy and not very efficient

END-WINDOW TUBE

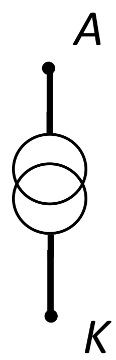
- Photocathode: thin semitransparent layer deposited on the interior of the glass tube end
- End window of the glass tube: favourable geometry, collection of light on the photocathode is easy and efficient

PhotoTube stationary I-V characteristics

- At low voltage V_{AK} the photocurrent collected at the anode is limited by the electron space charge effect
- As V_{AK} is increased the higher electric field reduces the space charge and the current increases
- As V_{AK} exceeds a saturation value V_{AKS} all photoelectrons are collected and the current is constant vs. V_{AK}
- The saturation value V_{AKS} increases with the optical power P_L on the detector
- Phototubes are operated biased into the current saturation region



PT stationary equivalent circuit:
photo-controlled current generator



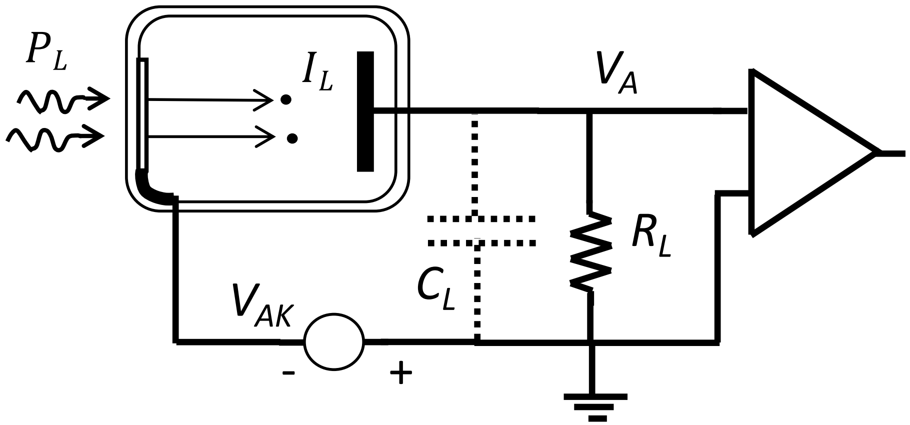
$$I_L = S_D \cdot P_L$$

Phototube Dynamic Response

PhotoTube Dynamic Response

Main causes that limit the dynamic response:

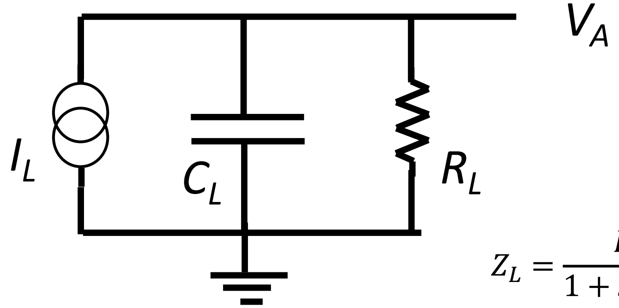
1. Transduction from light flux to detector current: the **SER** waveform $h_D(t)$ has finite-width T_D
2. **Load circuit:** it has a low-pass filter action, δ-response $h_L(t)$ with finite-width T_L



The δ-response from light power P_L to V_A has overall shape $h_P(t)$ resulting from the cascade

$$h_P(t) = h_D(t) * h_L(t)$$

PT equivalent circuit



$$Z_L = \frac{R_L}{1 + sR_L C_L}$$

the width T_P thus results from quadratic addition

$$T_P = \sqrt{T_D^2 + T_L^2} = \sqrt{T_D^2 + R_L^2 C_L^2}$$

and for well exploiting the fast intrinsic response $h_D(t)$ of a detector it is sufficient to have

$$\boxed{T_L = R_L C_L \leq T_D}$$

Load-circuit δ-response $R_L \cdot h_L(t)$ with

$$h_L(t) = 1(t) \frac{1}{R_L C_L} \exp\left(-\frac{t}{R_L C_L}\right)$$

Fast Response AND Wide Active Area

The light-to-current transduction by a phototube can be fairly fast, with SER pulse duration T_D around 1ns. For exploiting it, the load filtering must be adequately limited

$$\boxed{R_L C_L \leq T_D}$$

- for wide-band response low-value R_L is employed; typically, $R_L = 50\ \Omega$ to match a coaxial cable connection. With $T_D \approx 1$ns and $R_L = 50\ \Omega$, the above requirement implies $$\boxed{C_L \leq 20pF}$$
- The load capacitance C_L is sum of
  C_A input capacitance of amplifier (or other circuit) connected; it can be <1pF
  C_S stray capacitance of connections; it can be < 2pF
  C_D electrode capacitance; it depends on the area A_D of the photocathode
- C_D is small even for wide sensitive area A_D , because the dielectric is vacuum and the electrode spacing is wide. In plane geometry with cathode-to-anode spacing w_a

$$C_D = \varepsilon_o \frac{A_D}{w_a} \qquad\qquad (\varepsilon_o = 8{,}86 \frac{pF}{m})$$

e.g. with $w_a \approx 1cm$ it is $C_D[pF] \approx 0{,}09 A_D[cm^2]$. It's only $9pF$ for $A_D=100\ cm^2$

- **In conclusion:** a definite advantage of Vacuum Phototubes is that they offer **very wide sensitive area together with fast response**. We will see that with semiconductor photodiodes this is not achievable

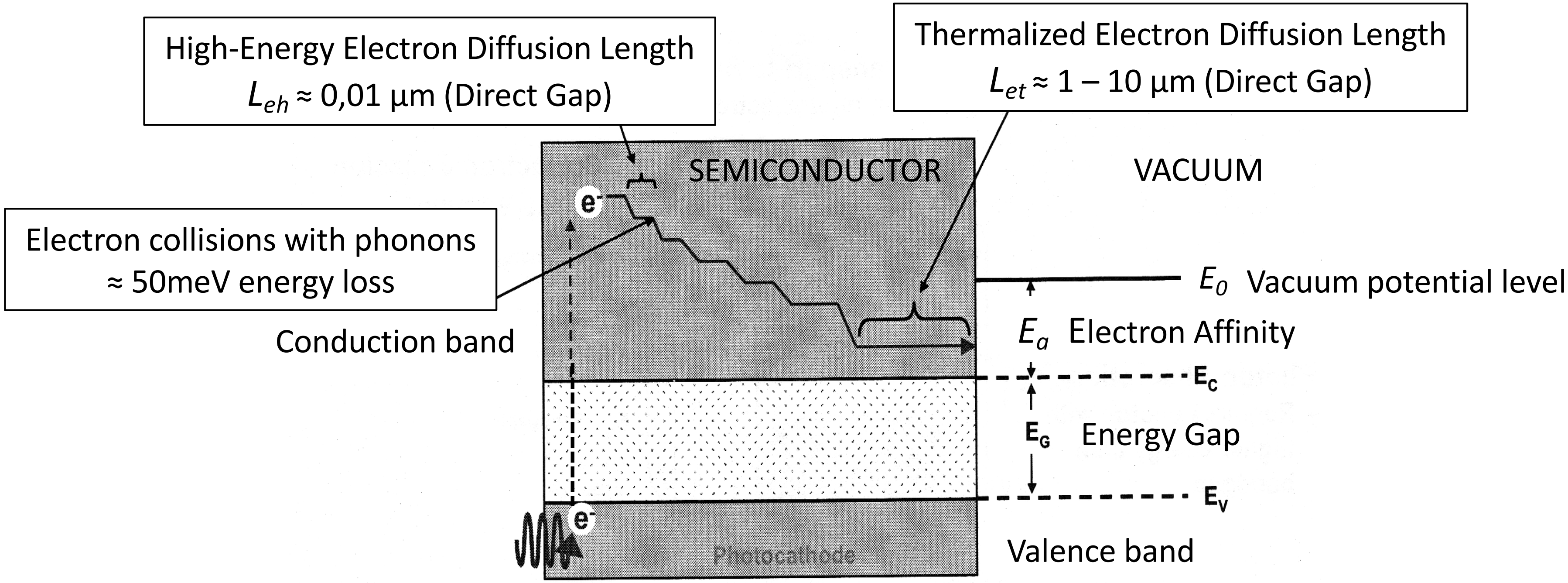
Electron Photoemission and Photocathode Technology

Photo-emission of electrons

It is a three-step process:

- free electron generation by photon absorption
- electron diffusion in the photocathode layer
- escape of electron into the vacuum

Suitable materials are semiconductors. Metals are unsuitable because of the high reflectivity, small diffusion length and low escape probability (high potential step from inside up to the vacuum level).



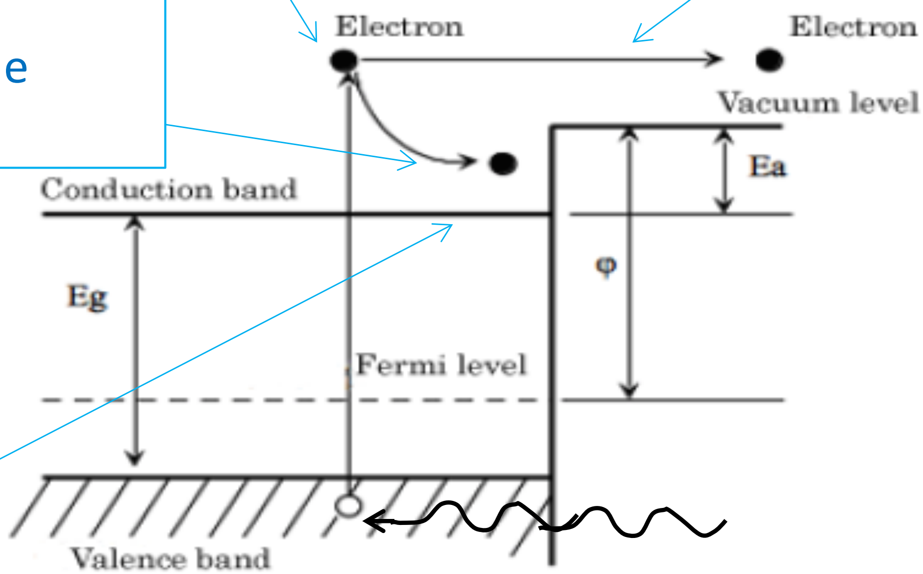
Ordinary photocathodes with positive E_a

1. Free electrons are generated with energy higher than the vacuum level and are slowed down by phonon collisions while diffusing a few 10nm

2. As long as an electron has energy level higher than the external potential it can escape into vacuum

3. If it does not escape, in a few ps it thermalizes down to the bottom of the conduction band

4. At the bottom of conduction band an electron can diffuse further a few μm and about 100ps before recombining (i.e. getting down to valence band) but it cannot escape any more into vacuum



Ordinary photocathodes with positive E_a

In order to offer good quantum detection efficiency, the photocathode material must fulfill some basic requirements.

- The inside-to-vacuum energy barrier $E_g + E_a$ must be smaller than the photon energy E_p . In the visible range $1{,}6\ eV < E_p < 3{,}1\ eV$ and $E_g \approx 1eV$ for semiconductors; therefore, the electron affinity must be limited

$$E_a \leq 1eV$$

- Electrons generated in deep layers are not emitted; escape probability is high only for electrons generated in a surface layer that is very thin, about a diffusion length L_{eh} of high-energy electrons. For a significant absorption in this layer the optical penetration length L_a must anyway be NOT much higher than L_{eh} ; for a high absorption it should be comparable

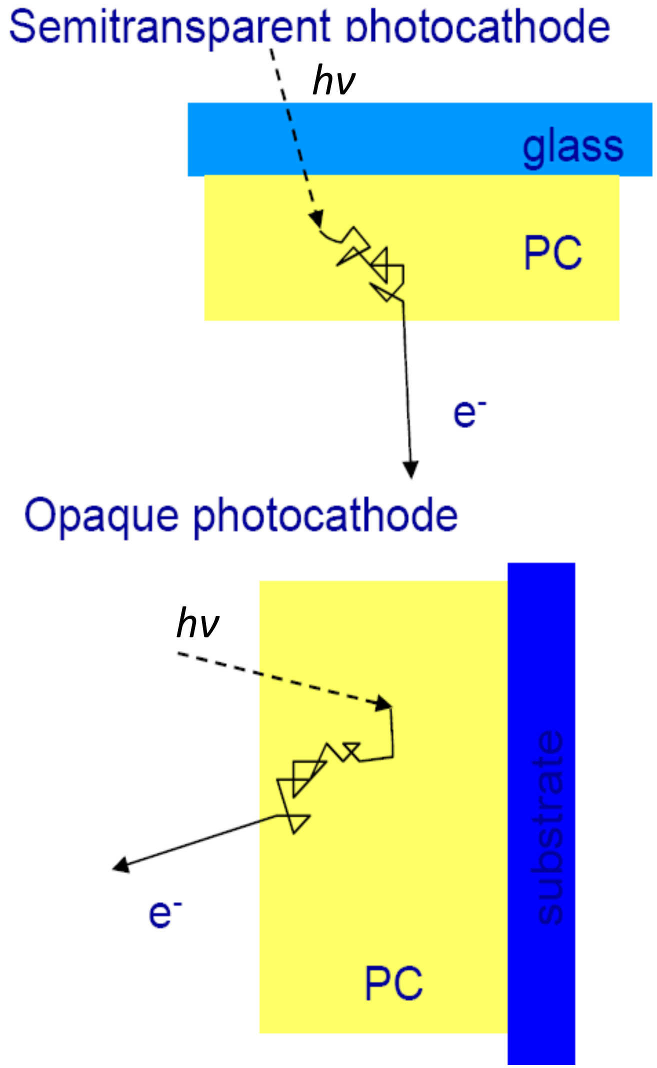
$$L_a \approx L_{eh}$$

In conclusion, the thickness of the photocathode layer contributing to the electron emission is intrinsically limited to about L_{eh} in any case. That is, the **active layer is very thin,** independent from the total thickness of the photocathode.

Semitransparent PhotoCathodes

The active layer of the photocathode is always very thin, also for thick cathodes deposited on a metal electrode.

This remark led to develop thin photocathodes (with thickness about ≈ L_{eh}) deposited on the interior of the glass tube in the end-window of the detector. They are called **semitransparent cathodes.** They are illuminated on the outer side through the glass window end emit photoelectrons from the inner side. They make possible and easy a much better optical collection than the side-window geometry



Semi-transparent photocathode

PhotoCathode Types

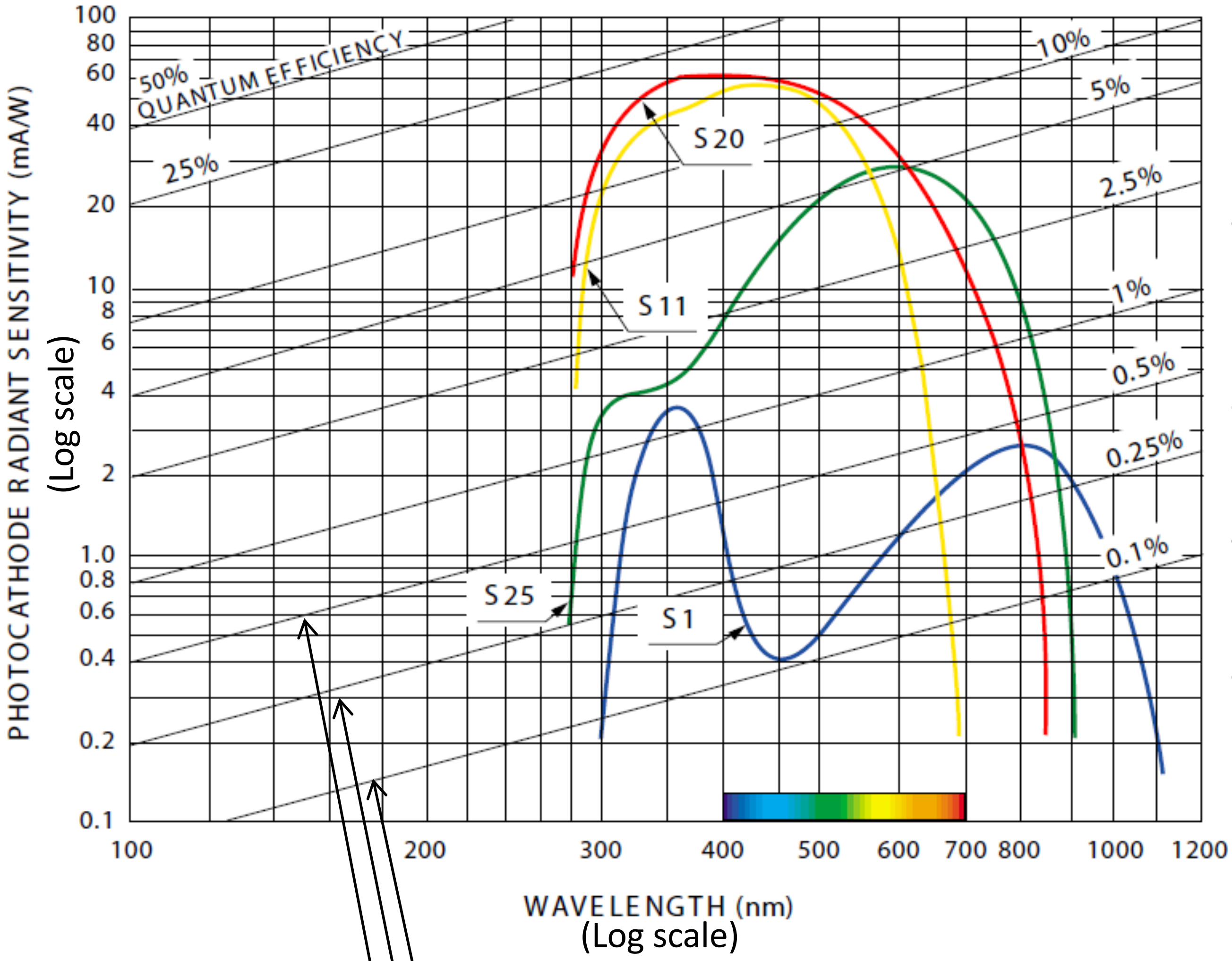
Classifications of Photocathode types are made by *industrial standard committees*. Most widely used is that by JEDEC (Joint Electron Devices Engineering Council US), which denotes cathode types S1, S2, ... and classifies them by spectral responsivity type (rather than by chemical composition or fabrication recipe).

- **S1** was introduced in the '30s and is still in use. The QE is low (peak $\eta_D \approx$ 0,4% at =800nm) but covers a wide spectrum in the IR. It is a matrix of Cesium oxide that includes silver microparticles and it's currently denoted Ag-O-Cs.

Highly efficient photocathodes for the visible range were introduced in the '50s and progressively developed employing compounds of alkali metals (Na, K, Cs, which have low work functions) and Antimony (Sb). Main types:

- **S11** ranges from 300nm to 600nm, peak $\eta_D \approx$15% at 450nm; alkali halide Cs_3Sb
- **S20** ranges from 300nm to 800nm, peak $\eta_D \approx$20% at 350nm; multi-alkali halide Na-K-Sb-Cs
- **S25** extends the range up to 800nm, peak $\eta_D \approx$5% at 600nm; multi-alkali Na-K-Sb-Cs like S20, but with a thicker layer that gives higher sensitivity in the red, at the cost of lower sensitivity in the blue-green

Radiant Sensitivity or Spectral Responsivity



PHOTOCATHODE TYPES

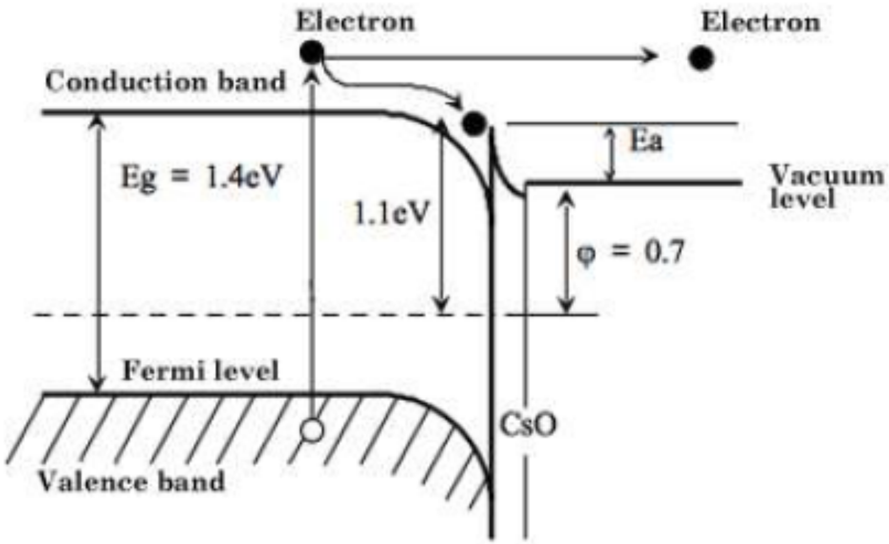
- S1 (Ag-O-Cs oldest type infrared-sensitive)
- S11 (Cs_3Sb alkali halide)
- S20 Na-K-Sb-Cs Multi-alkali halide
- S25 Multi alkali halide extended red sensitivity

NB: the auxiliary lines marked with Quantum Detection Efficiency (QE) in % make possible to read directly from the diagram also the QE

PhotoCathodes with negative E_a

Progress in semiconductor physics and technology led in the '70s to devise a new class of photocathodes, called photocathodes with Negative Electron Affinity (NEA)

- On a GaAs crystal substrate, a **few atomic layers of Cesium Oxide (*Cs-O*) are deposited and activated**, thus forming a very thin positive charge layer of Cs^+ ions.
- **The electric field** generated at the surface **curves downward the energy bands**: the vacuum potential level is now lower than the bottom of conduction band, i.e. the electron affinity E_a is negative
- Electrons can now escape into vacuum also when thermalized at the bottom of conduction band; QE is thus enhanced
- Photoelectron emission is obtained also with photons with lower energy E_p , down to the GaAs energy gap E_g



In conclusion: NEA cathodes offer **higher QE** value and **broader spectral range**, extending up to the absorption edge of GaAs (i.e. $\lambda \approx 900nm$ corresponding to the gap $E_g \approx 1{,}4\ eV$)

Detector Dark Current and Noise

Detector Dark Current

- A finite current is emitted by any photocathode even when kept in the dark, without any light falling on it.
- It is a spontaneous emission due to thermal effects (phonon-electron interactions in the cathode) and is called **Dark Current**.
- The dark current density j_B (per unit area of cathode) depends on the cathode type and on the cathode temperature. Typical values at room temperature are reported in the Table

PhotoCathode type	Dark Current density j_B in A/cm^2	Dark Electron Rate density n_B in electrons/s·cm^2
S1	$\approx 10^{-13}$	$\approx 10^{6}$
S11	10^{-16} - 10^{-15}	10^{3} - 10^{4}
S20 and S25	10^{-19} - 10^{-16}	1 - 10^{3}
GaAs NEA	10^{-18} - 10^{-16}	10 - 10^{3}

Detector Internal Noise

The total Dark Current is $I_B = j_B A_D$ where A_D is the area of the photocathode.

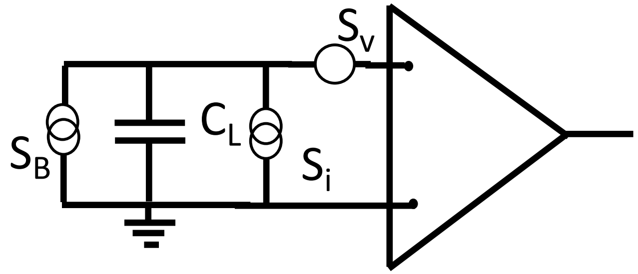
The shot noise of I_B is the photodetector unavoidable internal noise, with effective power density (unilateral)

$$\sqrt{S_B} = \sqrt{2qI_B} = \sqrt{2qj_B}\sqrt{A_D}$$

Typical values of $\sqrt{S_B}$ are reported in the Table

PhotoCathode type	Dark Current density j_B A/cm^2	Shot Noise Effective density $\sqrt{S_B}$ $pA/\sqrt{Hz}\sqrt{cm^2}$
S1	$\approx 10^{-13}$	$\approx 10^{-4}$
S11	10^{-16} - 10^{-15}	$\approx 10^{-5}$
S20 and S25	10^{-19} - 10^{-16}	$\approx 10^{-7} - 10^{-6}$
GaAs NEA	10^{-18} - 10^{-16}	$\approx 10^{-6}$

Role of the Detector Internal Noise



- We know that for operating with low-noise a high impedance sensor must be connected to a preamplifier with high input impedance and low input noise. The best available preamplifiers have current noise at room temperature

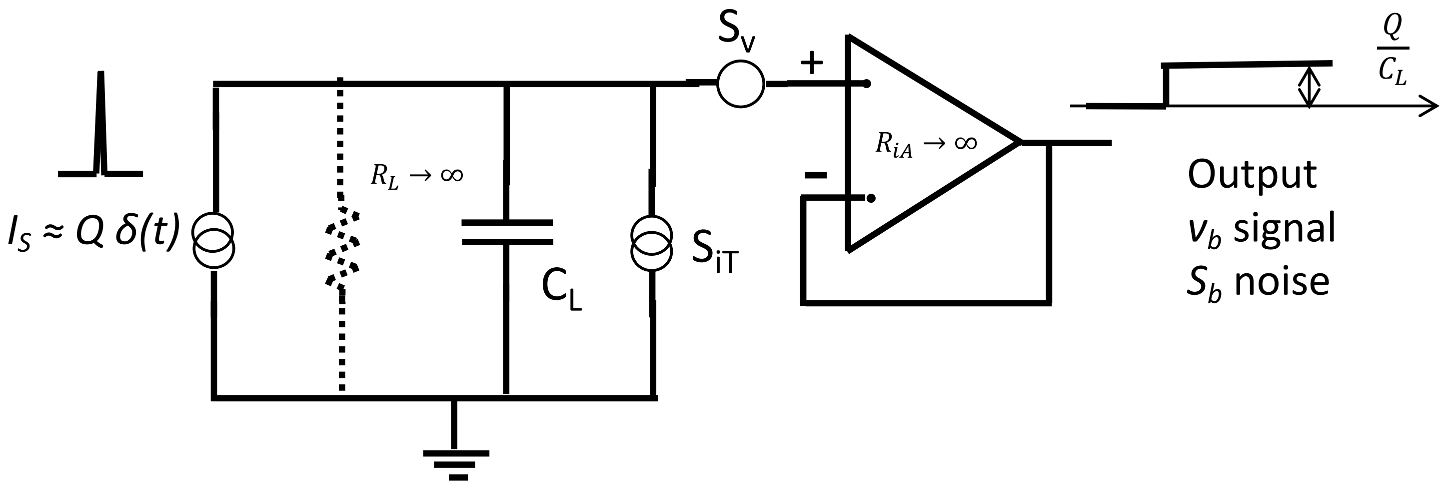
$$\sqrt{S_i} \approx 0{,}01 \frac{pA}{\sqrt{Hz}}$$

- **The circuit noise $\sqrt{S_i}$ is always dominant** and the detector **internal noise $\sqrt{S_B}$ plays in practice no role with any phototube**, even for detectors with S1 photocathodes (that have the highest noise) and even with very wide sensitive area (up to many square centimeters). In fact, for producing shot noise with power density higher than that of the circuit noise, the phototube dark current should be I_B>300pA, corresponding to an emission rate $n_B > 10^9$ electrons/s.
- **Vacuum tube photodiodes can thus be employed for operating at low noise without stringent limits to the sensitive area**. As we will see, this is a definite advantage over semiconductor photodiodes.

Low-noise preamplifiers for photodiodes

Voltage Buffer Preamplifier

- Photodiodes are high-impedance sensors (both the vacuum phototubes and the semiconductor photodiodes), hence for low-noise operation they must be connected to preamplifiers with high input resistance* $R_{iA} \rightarrow \infty$ (see slides in OPF2)
- Simple configuration: voltage buffer based on a high-input-impedance and low-noise amplifier



- C_L total load capacitance = C_D (detector cap.) + C_{iA} (amplifier cap.) + C_S (connection cap.)
- R_L total load resistance $\rightarrow \infty$
- S_v amplifier voltage noise
- S_{iT} total current noise = S_{iD} detector noise + S_{iA} amplifier noise (+ S_{iR} load resistor noise)

* R_{iA} = true physical resistance between the input terminals, not the dynamic input resistance including feedback effects

Voltage Buffer Preamplifier

Buffer voltage output:

Step signal

$$v_b(t) = \frac{Q}{C_L} \cdot 1(t)$$

Noise Spectrum

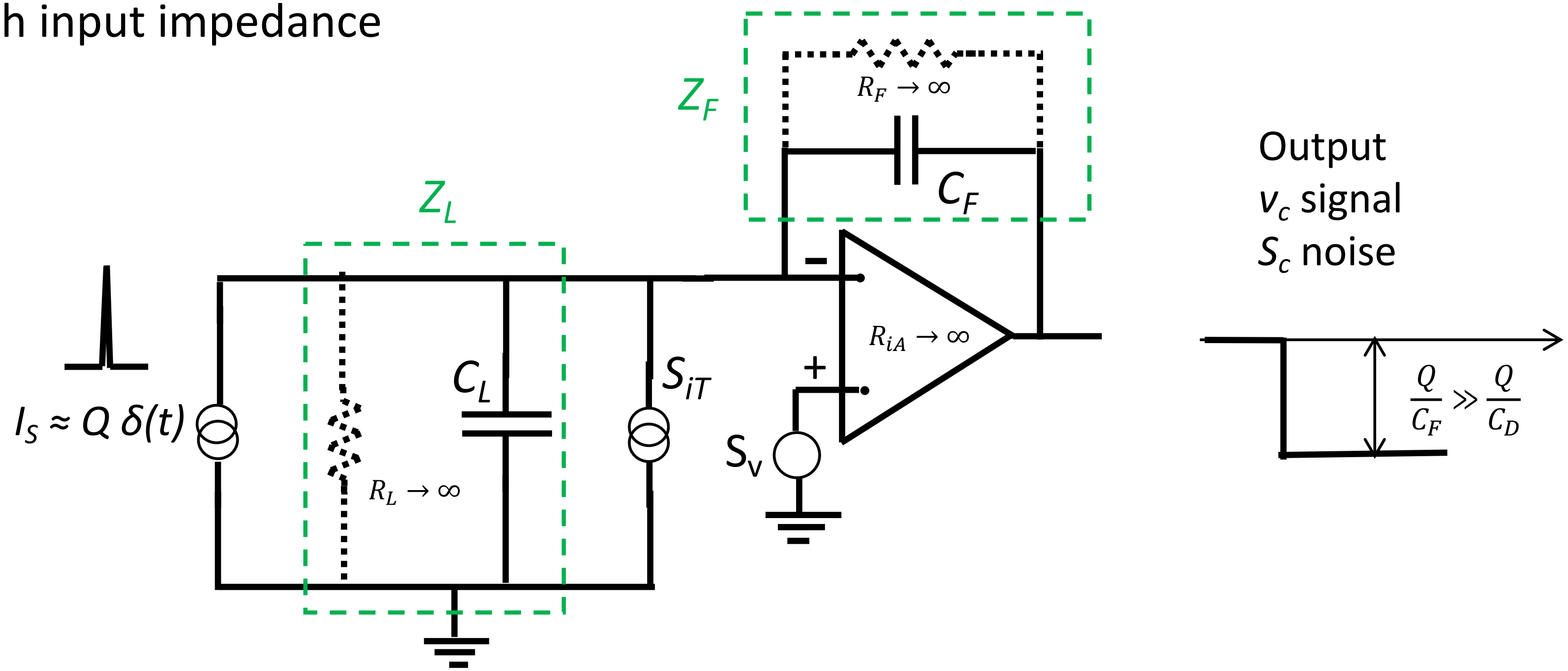
$$S_b = S_v + S_{iT} \frac{1}{\omega^2 C_L^2}$$

The buffer configuration has some noteworthy drawbacks.

- The signal amplitude Q/C_L is ruled by the total capacitance $C_L = C_D + C_{iA} + C_s$, whose value is not very small and not well controllable, particularly in cases where long sensor-preamplifier connections contribute a remarkable C_s .
  C_L may be different from sample to sample of the amplifier, even of the same amplifier model.
- With signals in high-rate sequence, the superposition of voltage steps may build-up and produce a significant decrease of the photodiode bias voltage. This may change the operating conditions and consequently the parameters and performance of the detector, particularly if the photodiode is biased not much above the saturation voltage.

Charge Preamplifier or Transimpedance Preamplifier

Alternative configuration: operational integrator based on a low-noise amplifier with high input impedance



- C_F capacitor in feedback. The **C_F value can be very small and is accurately set** by the capacitor component, because the inherent stray capacitance between output and input pins of the amplifier is negligible. Therefore, **one can work with $C_F << C_L$**
- R_F feedback resistor → ∞
- C_L total load capacitance = C_D (detector cap.) + C_{iA} (amplifier cap.) + C_S (connection cap.)
- R_L total load resistance → ∞
- S_v amplifier voltage noise
- S_{iT} total current noise = S_{iD} detector noise + S_{iA} amplifier noise (+ S_{iR} load resistor noise)

Charge Preamplifier or Transimpedance Preamplifier

Output Signal:

in frequency domain $V_c = -QZ_F = -\frac{Q}{j\omega C_F}$ in time $v_c(t) = -\frac{Q}{C_F} \cdot 1(t)$

With respect to the buffer, the amplitude is greater by the gain factor $G_c = C_L/C_F \gg 1$

$$\boxed{|v_c| = \frac{Q}{C_F} = \frac{C_L}{C_F} \cdot \frac{Q}{C_L} = \frac{C_L}{C_F} \cdot |v_b| = G_c \cdot |v_b|}$$

Advantages:

- The higher signal makes less relevant the noise of the following circuits
- The signal amplitude is ruled by the well controlled and stable C_F , no more by the other capacitances C_D , C_{iA} and C_s
- The detector terminal is connected to the amplifier virtual ground, hence it stays at constant bias voltage even with signals in high-rate sequence

The noise analysis (see next slide) confirms that these advantages are obtained without degrading the S/N. The charge amplifier configuration thus is the solution of choice in most cases met in practice.

Charge Preamplifier or Transimpedance Preamplifier

Output Noise Spectrum :

- the current noise S_{iT} is processed by the same transfer function as the current signal
- the voltage noise S_v is processed with the transfer function from non-inverting input to amplifier output.

Denoting by Z_L the load impedance and by Z_F the feedback impedance

$$S_c = S_v \left|1 + \frac{Z_F}{Z_L}\right|^2 + S_{iT}|Z_F|^2$$

in our case $Z_L \approx 1/j\omega C_L$ and $Z_F \approx 1/j\omega C_F$ so that

$$S_c = S_v \left|1 + \frac{C_L}{C_F}\right|^2 + S_{iT}\frac{1}{\omega^2 C_F^2} = \left(\frac{C_L}{C_F}\right)^2 \left[S_v\left(1 + \frac{C_F}{C_L}\right)^2 + S_{iT}\frac{1}{\omega^2 C_L^2}\right]$$

if $C_F/C_L << 1$, with good approximation it is

$$\boxed{S_c \approx \left(\frac{C_L}{C_F}\right)^2 \left[S_v + S_{iT}\frac{1}{\omega^2 C_L^2}\right] = \left(\frac{C_L}{C_F}\right)^2 S_b = G_c^2 S_b}$$

With respect to the buffer, the signal and noise thus benefit of the same gain G_c : therefore, the attainable S/N is the same with the charge preamplifier as with the voltage buffer preamplifier

NEP and Detectivity

NEP and Detectivity

- Evaluations and comparisons of Photocathodes are currently based on the **Noise Equivalent Power NEP**, a figure of merit that takes into account the photon detection efficiency and the detector dark-current noise, but not the preamplifier noise.
- NEP is defined with reference to a situation where **the limit** to the minimum measurable signal is **set by the internal noise of the detector** and not by the electronic circuit noise. We have seen that this is **NOT the case with PhotoTubes** but we will see that **it is the case with PhotoMultiplier Tubes**. NEP was devised as an figure of merit for comparing objectively the intrinsic quality of different detectors.

Let a photocathode have area A_D , signal current I_p and Dark Current I_B with area density j_B . Employing a filter with bandwidth (unilateral) Δf we have noise

$$\sqrt{\overline{i_n^2}} = \sqrt{2qI_B\Delta f} = \sqrt{2qj_B}\sqrt{A_D}\sqrt{\Delta f} \qquad \text{and} \qquad \frac{S}{N} = \frac{I_p}{\sqrt{\overline{i_n^2}}}$$

The minimum measurable current signal $I_{p,min}$ (corresponding to S/N=1) is

$$I_{p,\,min} = \sqrt{\overline{i_n^2}} = \sqrt{2qj_B}\sqrt{A_D}\sqrt{\Delta f}$$

For illumination with optical power P_p at a given λ the Detector Responsivity is

$$S_D = \frac{I_p}{P_p} = \eta_D \cdot \frac{\lambda}{\frac{hc}{q}} = \eta_D \cdot \frac{\lambda[\mu m]}{1{,}24}$$

NEP and Detectivity

- NEP is defined as the input optical power $P_{p,\,min}$ corresponding to the minimum measurable signal

$$NEP = P_{p,\min} = \frac{I_{p,\min}}{S_D} = \frac{\sqrt{\overline{i_n^2}}}{S_D} = \frac{\sqrt{2qj_B}\sqrt{A_D}\sqrt{\Delta f}}{S_D}$$

  In essence: NEP = detector noise referred to the input (in this case the **optical input**).

- However, the NEP is not a fully objective figure of merit for assessing and comparing the quality of photocathodes: in fact, **cathodes of equal quality have different NEP if they have different area**. Furthermore, the NEP is an inverse scale, that is, the best photocathodes have the lowest NEP figures.

- A different figure named Detectivity D* was therefore derived from the NEP by
  a) considering the NEP value normalized to unit sensitive area ($A_D = 1cm^2$) and to unit filtering bandwidth (Δf = 1Hz)
  b) defining the Detectivity D* as the reciprocal of the normalized NEP

$$\boxed{D^* = \frac{\sqrt{A_D}\sqrt{\Delta f}}{NEP}}$$

that is

$$D^* = \frac{S_D}{\sqrt{2qj_B}} = \eta_D \cdot \frac{\lambda[\mu m]}{1{,}24}\frac{1}{\sqrt{2qj_B}}$$