Agenda

- Phenomenological model of matter ionization by particles
  - Electronic stopping
  - Bethe-Bloch Formula
  - Examples
  - Range and specific ionization
  - Stopping power curves, energy loss in thin foils

- Detection of ionizing radiation (photons and charged particles)
  - Gas amplification detectors (Ionization chamber, proportional counter, Geiger counter)
  - Spurious response of gas counters to photons
  - Solid-state detectors (Ge, Li surface barrier α detectors)
    - ❖ ANSEL experiment α spectroscopy

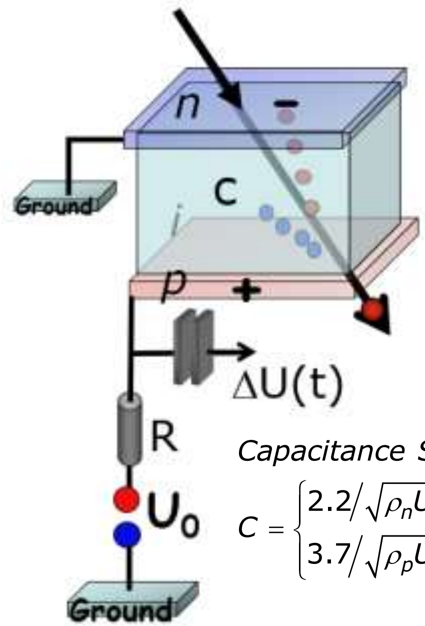
- Electronic signal processing: Detection of simultaneous emission events with multiple detectors
  - Photon spatial (angular) correlations in annihilation and nuclear γ–γ cascades
  - Coincidence measurements, electronics,
    - ❖ ANSEL PET experiment
  - Absolute activities

Reading: Knoll Chs. 11,13

Ionization Chambers (Solid-State and Gas Medium)

General principle: Radiation dissipates energy ***E*** via production of electron-ion (e^-, h^+) pairs in a medium enclosed between electrodes (Anode, Cathode). Electronic ***E*** signal picked up at A or C.

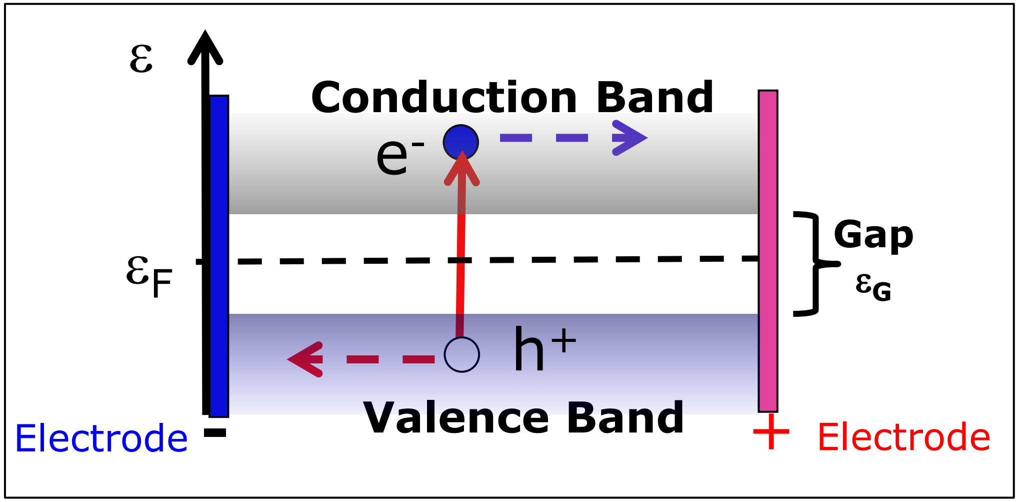
Gas volume between capacitor *C* electrodes.
Energy ***E*** → $\boldsymbol{N}_{\text{ion pairs}}=E/\varepsilon_{ip}(\text{gas})$



Capacitance Si :

$$C = \begin{cases} 2.2/\sqrt{\rho_n U_0} \;\; pF/mm^2 \\ 3.7/\sqrt{\rho_p U_0} \;\; pF/mm^2 \end{cases}$$

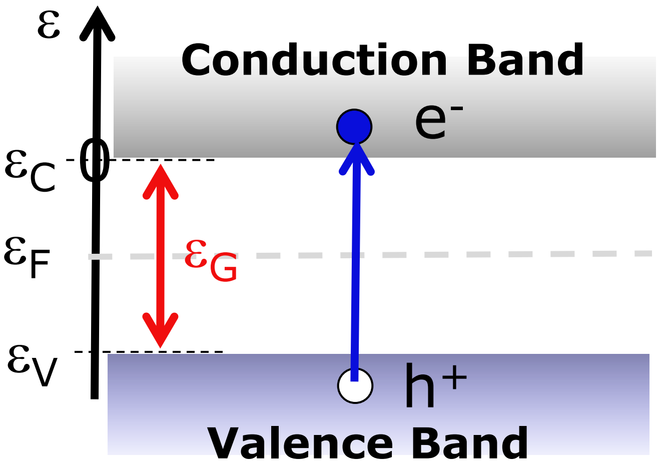
Semiconductor *n-, p-, i-types Si, Ge, GaAs,..*
→**Band structure of solids** ***VB*** gap ***CB***.



Initial (dark) state: No free charge carriers !

Ionization lifts e^- up to CB, leaves hole h^+ in VB → free charge carriers, produce ***ΔU(t)~E***.

Particles and Holes in Pure Semi-Conductors



Fermi gas of electrons (and holes)
Fermion statistics @ temperature ***T***:

n_e, n_h = # of occupied e^- or h^+ states
$f_e, f_h \le 1$ occupation numbers

$$n_e(\varepsilon) = \frac{(2m)^{2/3} V}{2\pi^2\hbar^3}\sqrt{\varepsilon}\cdot f_e(\varepsilon) \quad V = volume$$

$$n_h(\varepsilon) = \frac{(2m)^{2/3} V}{2\pi^2\hbar^3}\sqrt{|\varepsilon|}\cdot f_h(\varepsilon) \quad n_e = n_h!!$$

$$\varepsilon_F = \varepsilon_C - \varepsilon_G/2 = -\varepsilon_G/2 \quad for\ \varepsilon_C := 0$$

$$f_e(\varepsilon) = \left[1 + \exp\left(\frac{\varepsilon - \varepsilon_F}{kT}\right)\right]^{-1}$$

$$\xrightarrow[kT \approx 25meV \ll \varepsilon_G]{} \exp\left(-\frac{\varepsilon + \varepsilon_G/2}{kT}\right)$$

$$\langle n_e^2\rangle = \langle n_e n_h\rangle = \left(\frac{(2m)^{2/3} V}{2\pi^2\hbar^3}\right)^2 \langle\varepsilon\rangle \exp\left(-\frac{\varepsilon_G}{kT}\right)$$

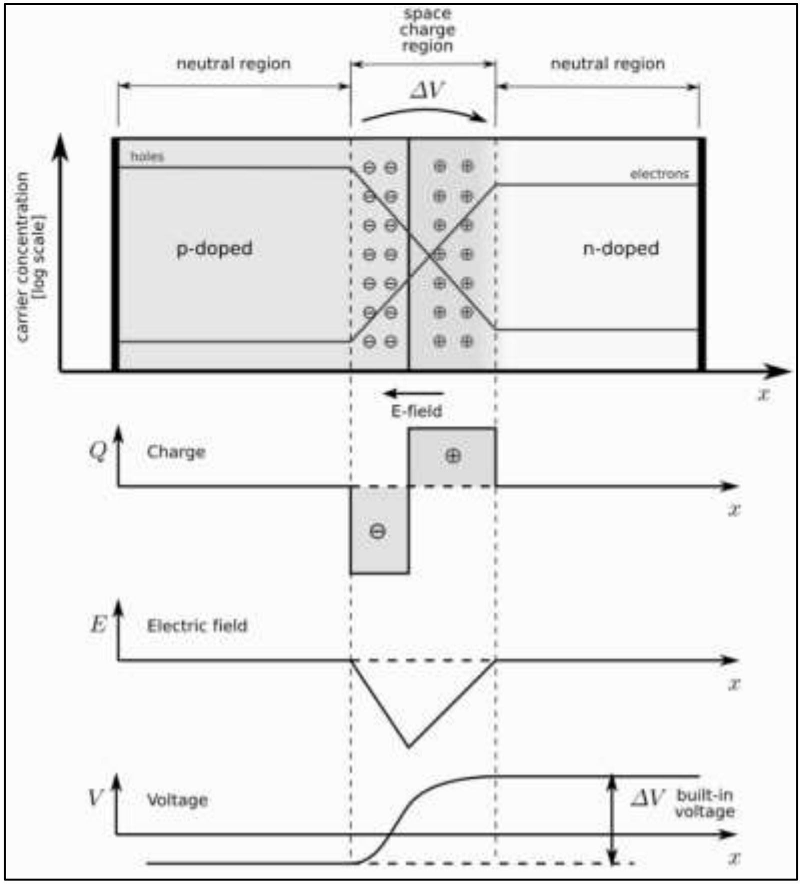
$$e^- : f_e(\varepsilon) = \left[1 + \exp\left(\frac{\varepsilon + \varepsilon_G/2}{kT}\right)\right]^{-1}$$

$$h^+ : f_h(\varepsilon) = \left[1 + \exp\left(\frac{-\varepsilon + \varepsilon_G/2}{kT}\right)\right]^{-1}$$

Small gaps ε_G (Ge) → high thermal currents. Reduce by cooling.

$$\langle n_e\rangle_{rms} \sim \exp\left(-\frac{\varepsilon_G}{2kT}\right) \propto \textit{noise generating conductivity at } T$$

Semiconductor Junctions and Barriers

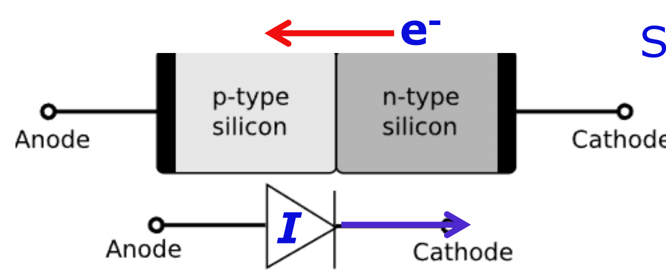


Need detector for rad-induced free charges → otherwise, no free carriers allowed.

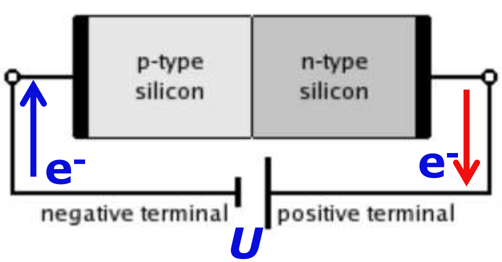
Need perfect *i*-type (intrinsic) Si = chemical Group IV with no free charge carriers.

Trick: Deplete part of combination (SC junction)
n-type Si: by doping with *Li or* Group V e^- donor atoms (*P, Sb, As*),
p-type Si: by doping with Group III e^- acceptor atoms *(B,Al,..)*.

Junctions diffuse ***e***$^-$ donors and acceptors into ***Si*** bi-layer bloc from different ends.
Diffusion at ***junction*** → e^-/h^+ annihilation → *space charge-zone* depleted of free carriers



SC Diode

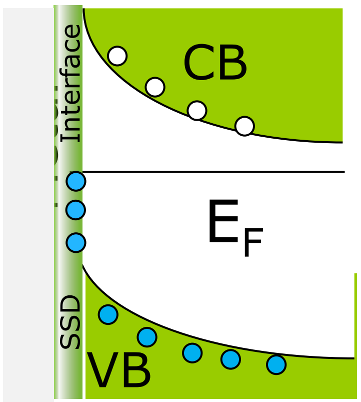


Reverse bias stabilizes depletion zone

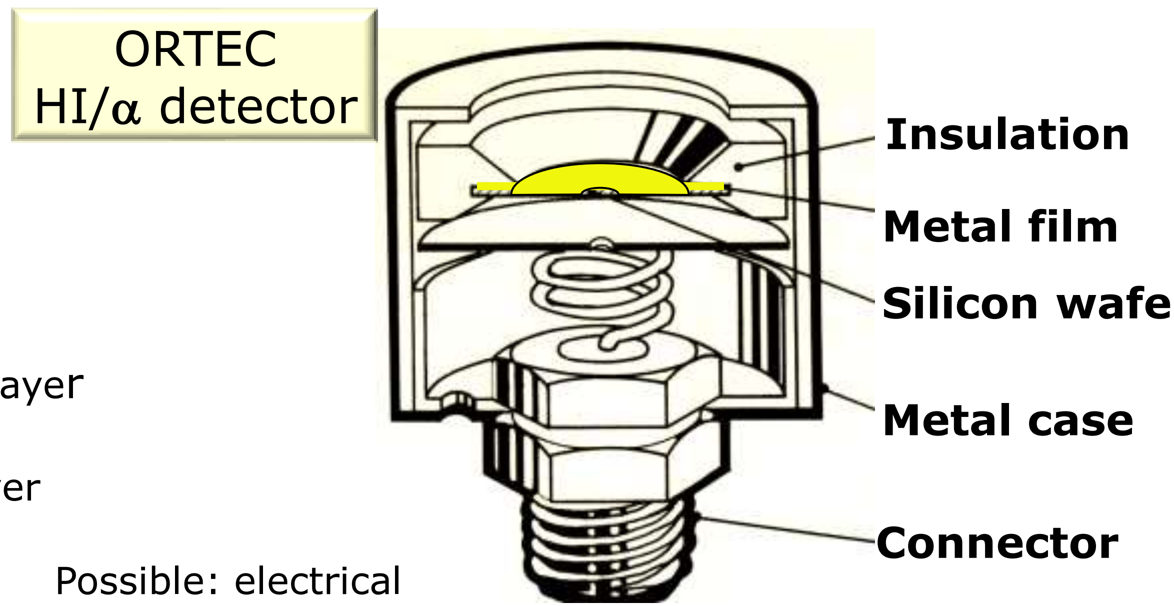
Electrons move easily through the junction *from n to p but not from p to n*, and the reverse is true for holes.

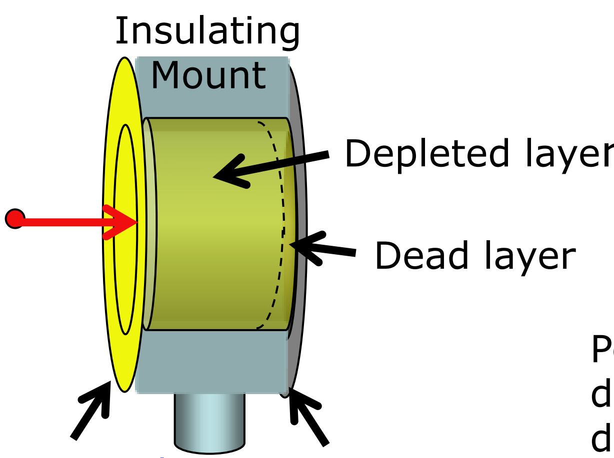
Surface Barrier Detectors

Semiconductor/ Metal Junction



Thin metal film on Si surface produces space charge (SSD surface states) = effective barrier (contact potential) → depleted zone with no free charges. Apply reverse bias to increase depletion depth. Free charge carriers created from incident radiation → ΔV signal

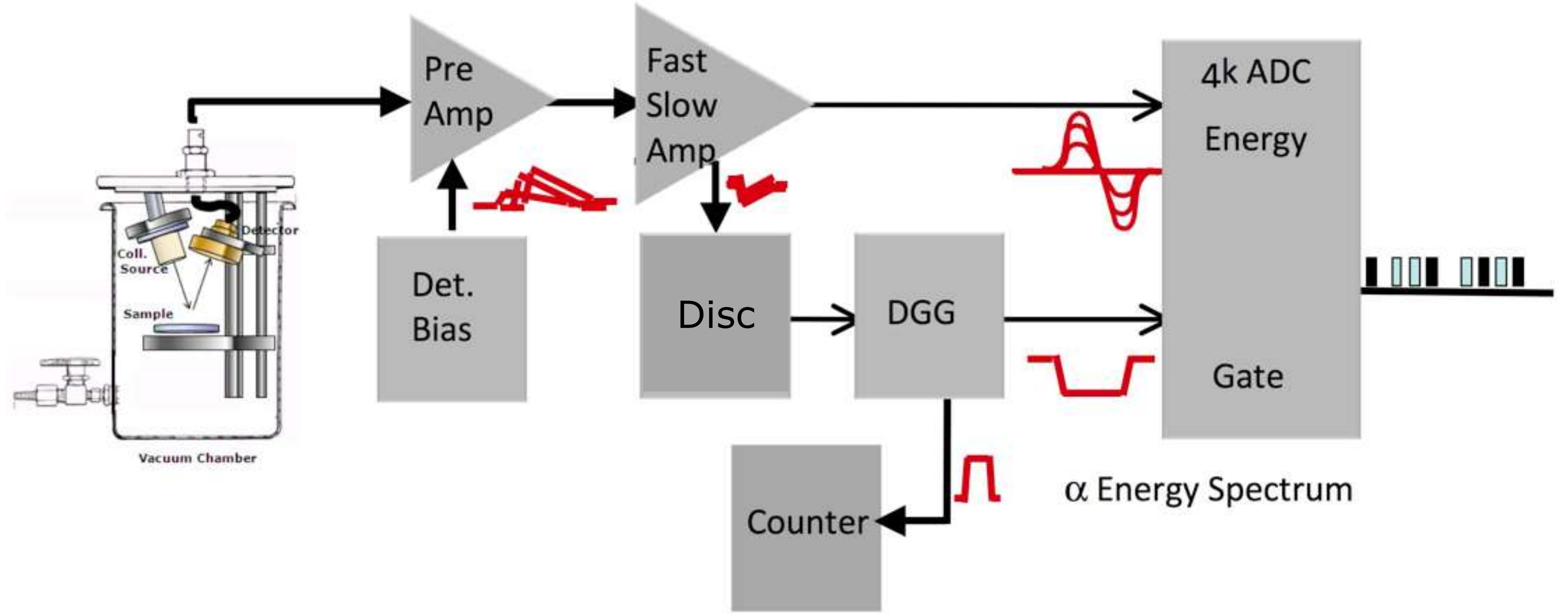




Ground +Bias
Front: Au Back: Al
evaporated electrodes

Possible: electrical
depletion depth ~ 100μ
dead layer $d_d \leq$ 1μ
V ~ 0.5V/μ
Over-bias reduces d_d

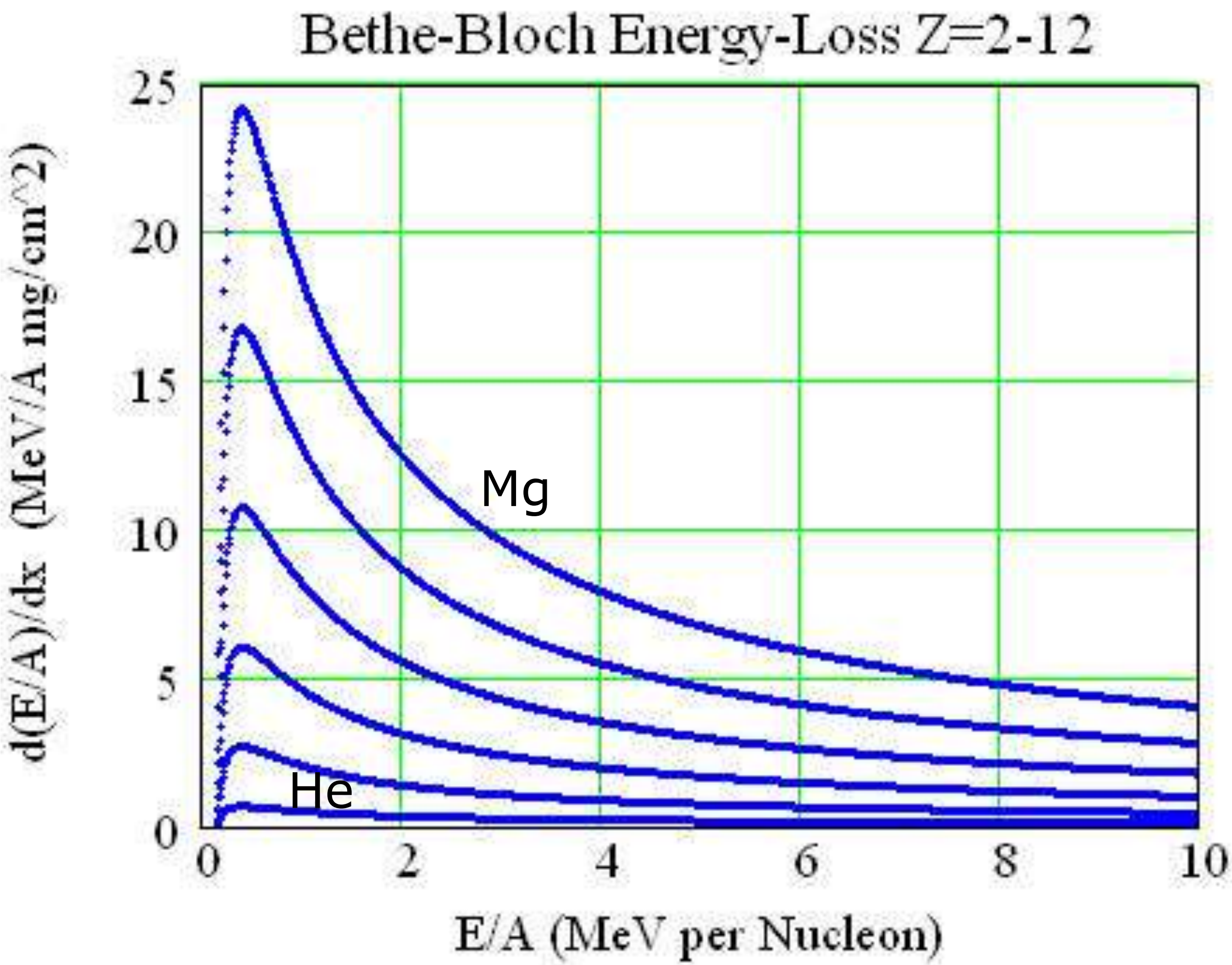
ANSEL Experiment: Alpha Spectroscopy



- Destruction-free material testing:
  Use Bethe-Bloch theory to determine thickness of thin films.
  (Use Rutherford-backscattering to determine material composition.)

- Demonstrate & explain interaction of particles with matter
- Calibration and optimization of signal processing of silicon detectors.
- Linearity measurements using a pulse generator.

Theoretical E-Loss in Thin Absorbers



Units MeV/Nucleon

Loss:
MeV/A per mg/cm^2

Bragg maximum

Semi-quantitative only: Expt values smaller both at small and large energies
→ recharging effects for projectile

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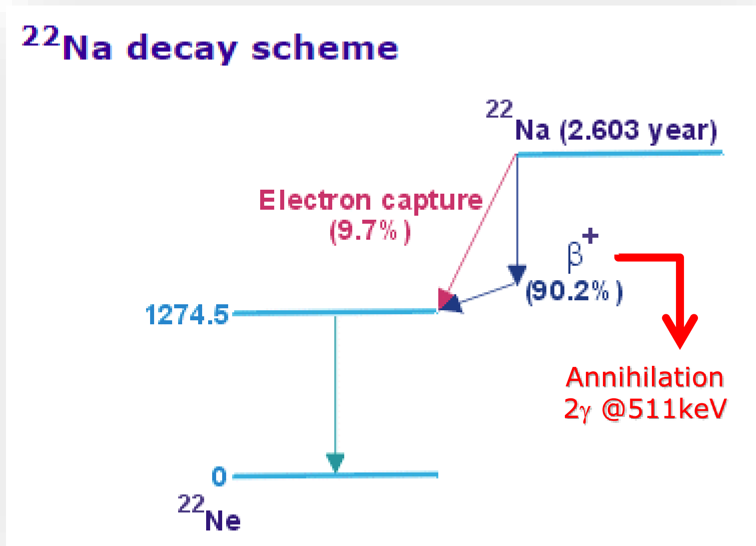
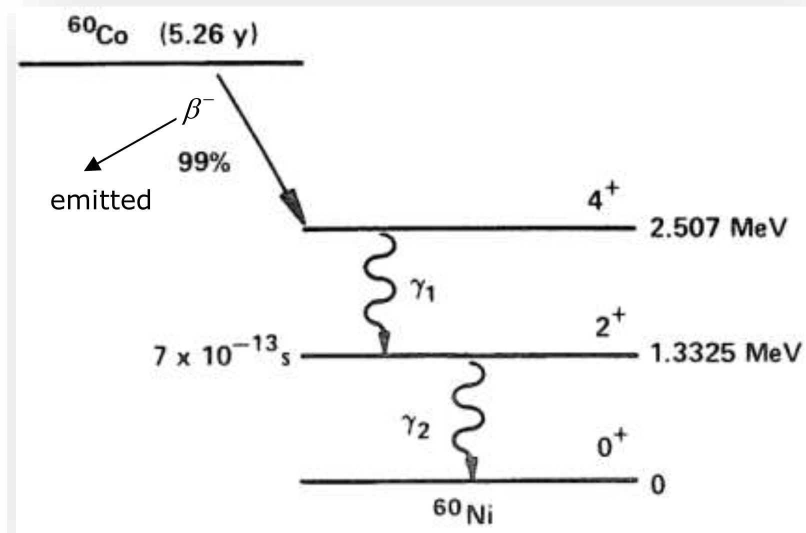
Gamma-Gamma-Correlations

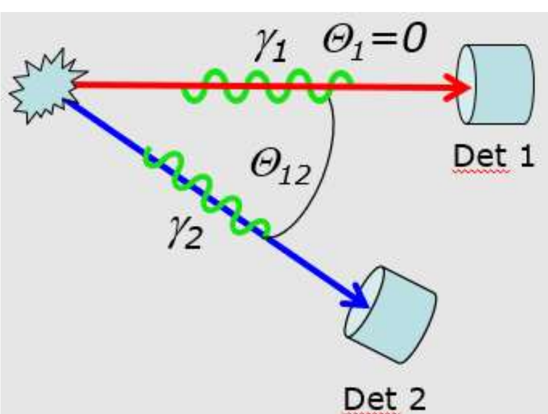




$QM\ \ prediction\ \ for\ P_{12}(\Theta_{12}) \rightarrow Nphys$

Detection probabilities

$$P_i = \varepsilon_i \cdot \frac{\Delta\Omega_i}{4\pi};\ \Delta\Omega_i = \frac{F_{detector\ i}}{R^2_{source-detector\ i}}$$



Absolute Activity Measurement

2 directionally uncorrelated γ-rays detected as singles ($\dot{N}_1$ and $\dot{N}_2$) or coincidences ($\dot{N}_{12}$).

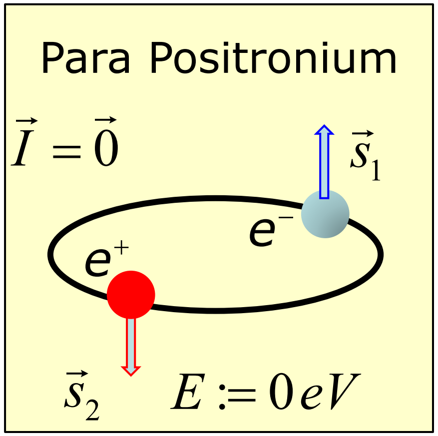
$$\dot{N}_1 = A \cdot P_1 \qquad \dot{N}_2 = A \cdot P_2 \qquad individual\ rates$$

$$P_{12} = P_1 \bullet P_2 \qquad \dot{N}_{12} = A \cdot P_{12} \qquad uncorr.\ coinc\ rate$$

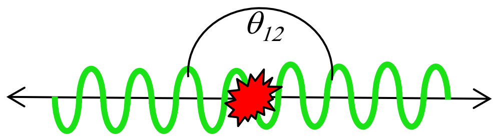
$$A = \frac{\dot{N}_1 \cdot \dot{N}_2}{\dot{N}_{12}} = \frac{A \cdot P_1 \cdot A \cdot P_2}{A \cdot P_{12}} \qquad singles / coinc$$

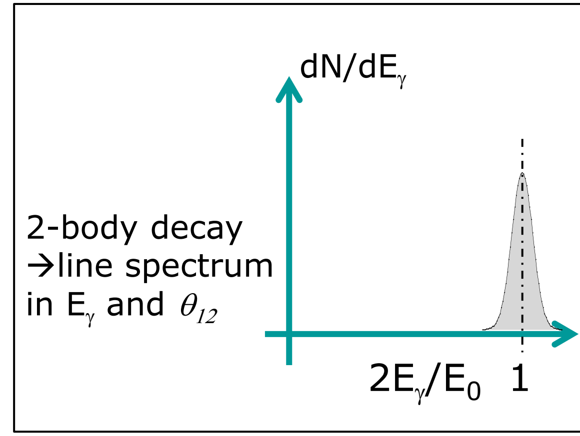
$A\ error\ ??$

Positronium and e^+-e^- Annihilation



Decay at rest:
$2E_\gamma \approx E_0 \approx 1.022\ MeV$
2-body decay → $\theta_{12} \approx 180^0$

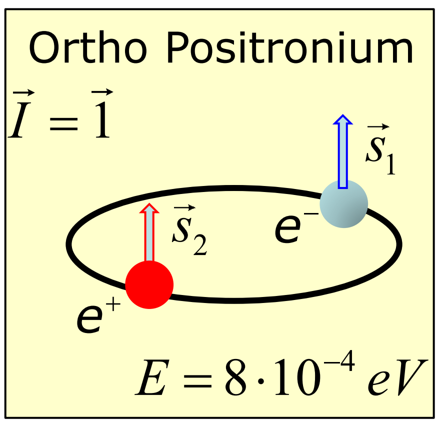


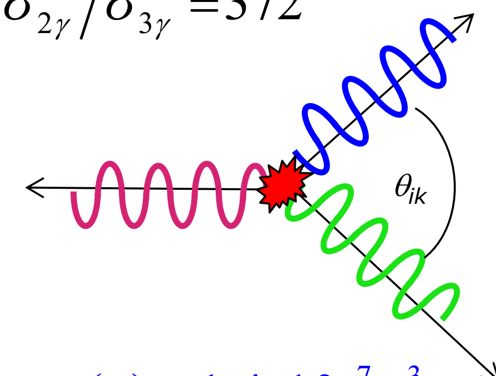


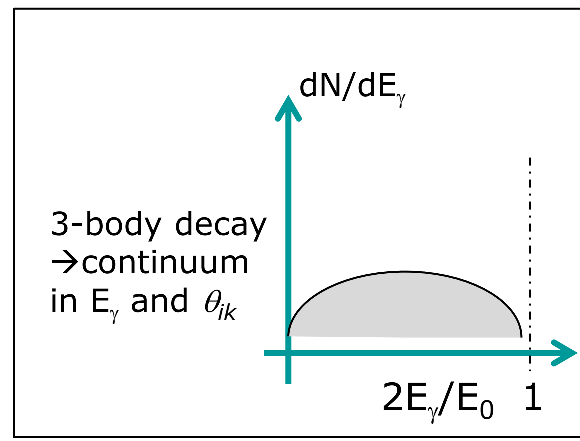
$$\tau_{2\gamma}(n) = 1.25 \cdot 10^{-10}\, n^3 \sec$$

n = *principal quantum* # of *positronium molecule*

$$\sigma_{2\gamma} / \sigma_{3\gamma} = 372$$





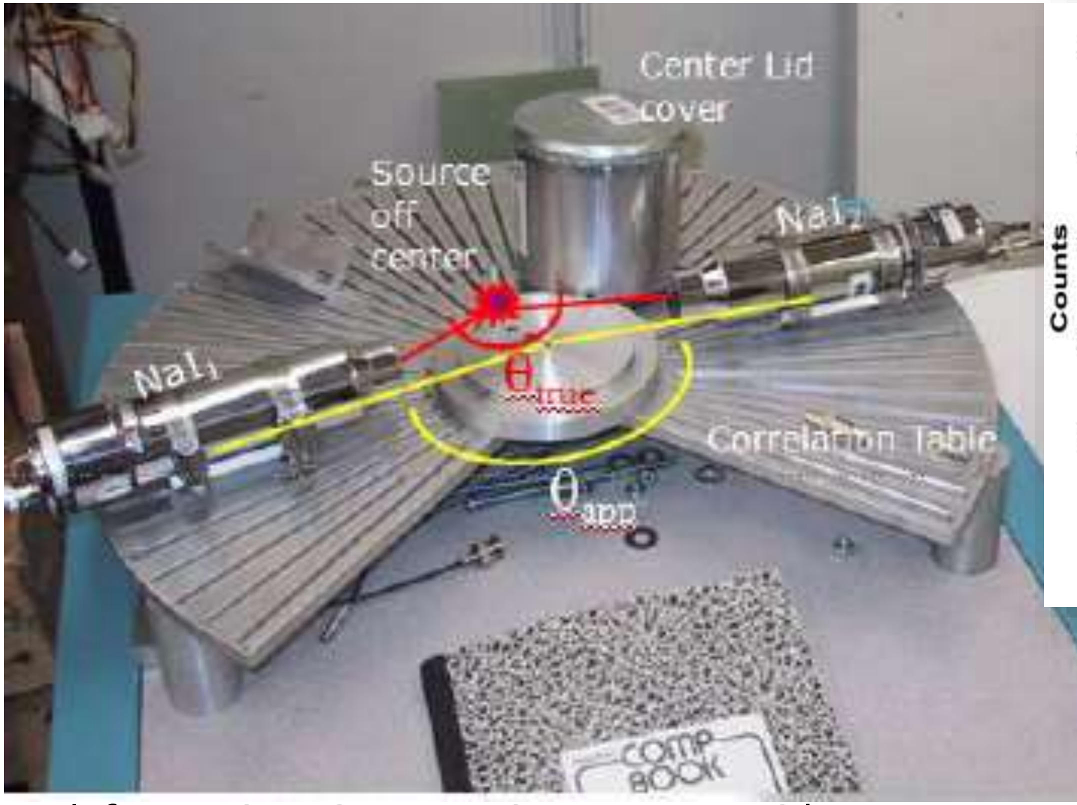


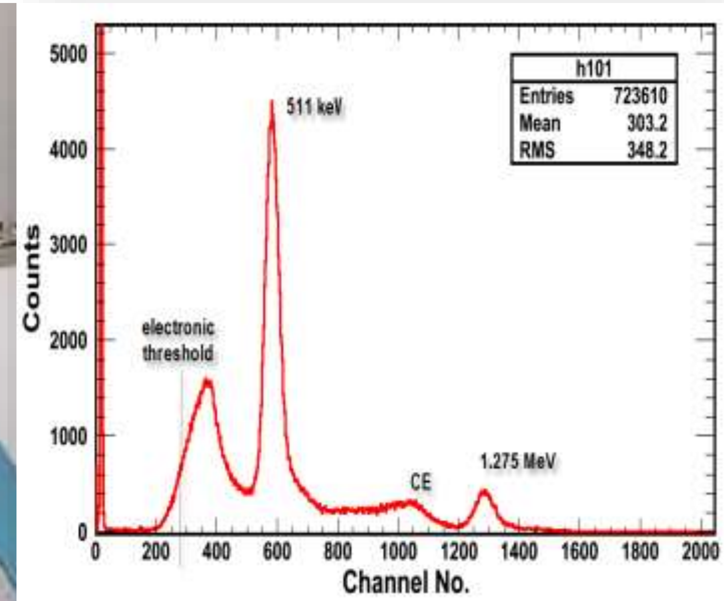
$$\tau_{3\gamma}(n) = 1.4 \cdot 10^{-7}\, n^3 \sec$$

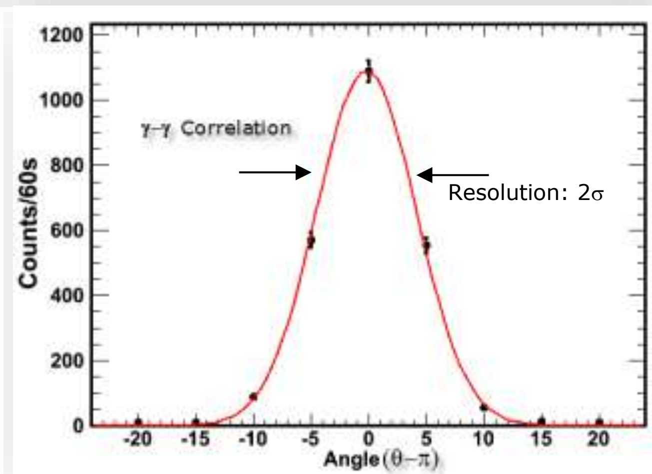
$$\sigma_{2\gamma} = \pi r_0^2 \cdot \frac{\upsilon_{e^+e^-}}{c}; \quad \sigma_{2\gamma} / \sigma_{3\gamma} = 372$$

$r_0 = 2.818\, fm$, *class. electron radius*

ANSEL Angular Correlation Experiment





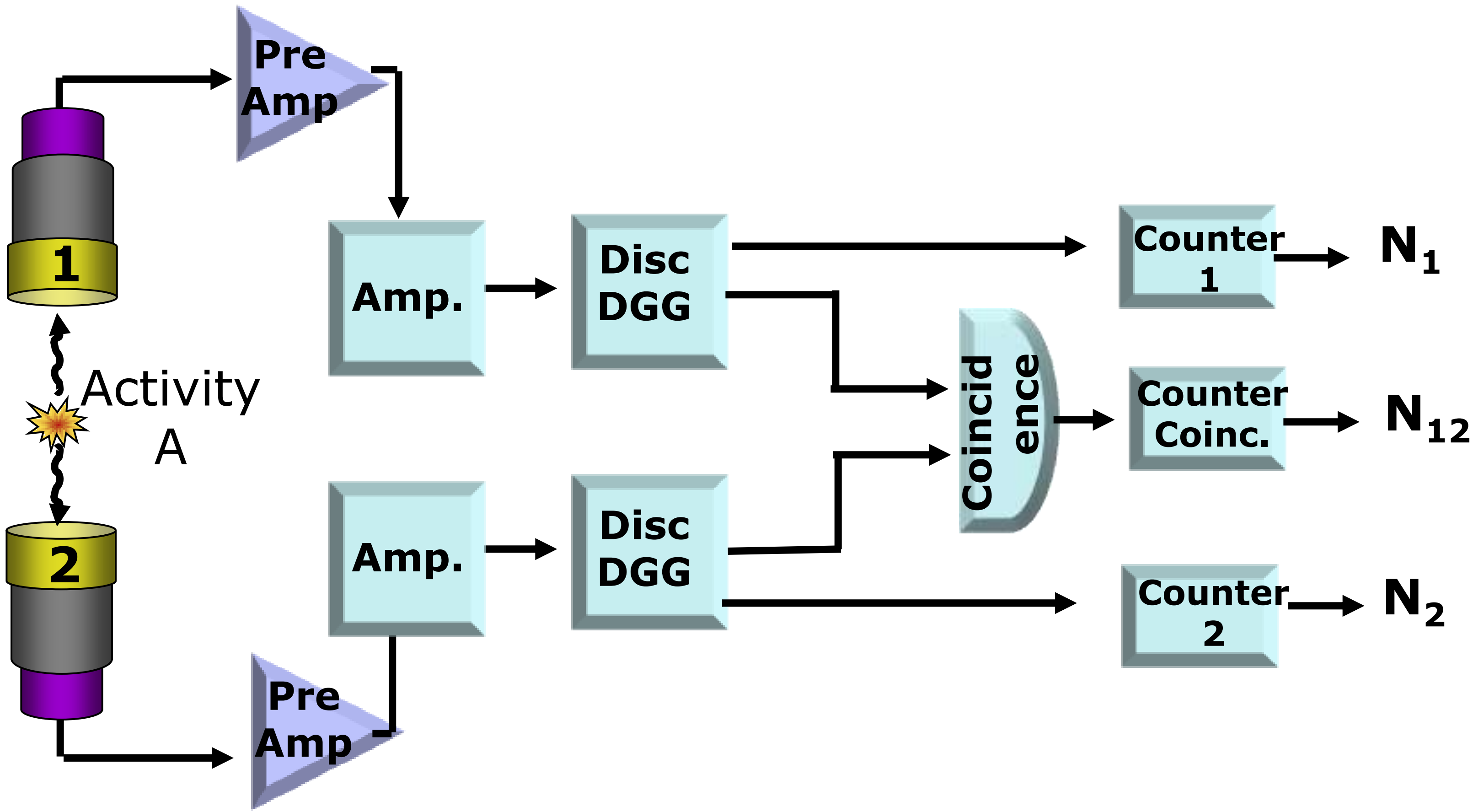


Top left: PET imaging experiment setup with two 1.5"x1.5" NaI(*Tl*) detectors (BICRON) on a slotted correlation table. A "point-like" ^{22}Na γ source can be hidden from view.
Top right: ^{22}Na γ spectrum measured with NaI_1.
Bottom right: $\gamma-\gamma$ angular correlation measurement.

Second correlation setup: NaI*(Tl) vs. HP*Ge

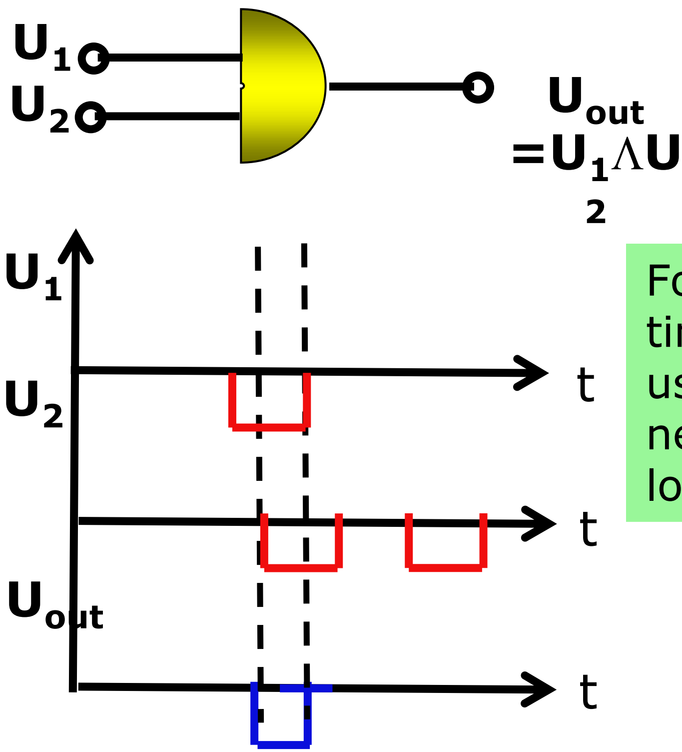
E_γ-Ungated Coincidence Measurement

Activity $A=\lambda N$ [disintegrations/time], simultaneous emission of (angular-) uncorrelated radiation types: ***i =1,2*** per event, resp. detection probabilities P_i



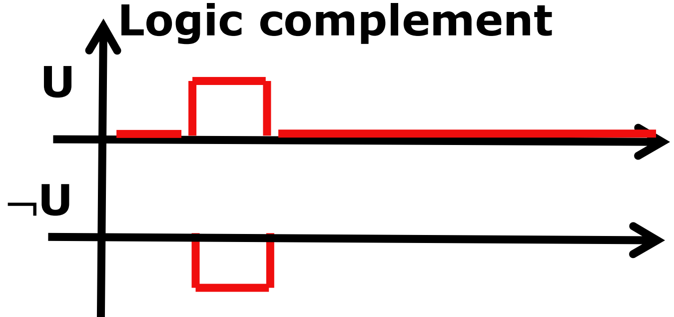
Digital Logic Modules

AND Overlap Coincidence



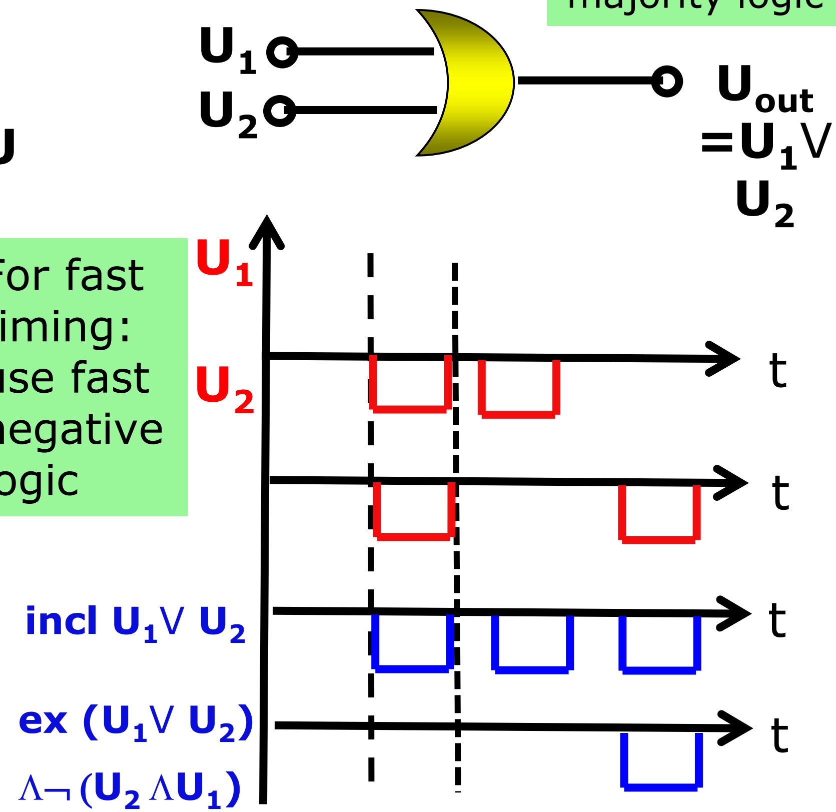
For fast timing: use fast negative logic

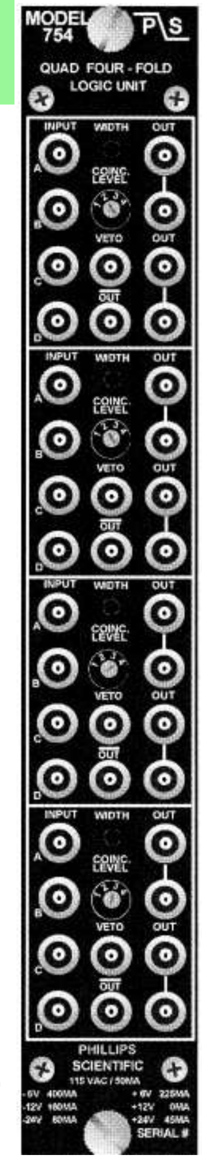
Logic complement

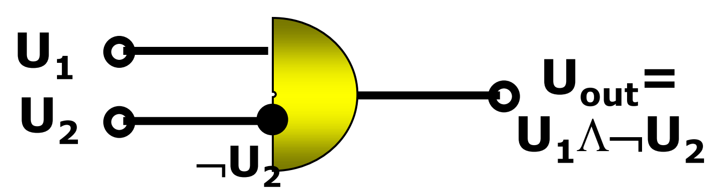


OR (inclusive)

Quad 4-fold majority logic unit



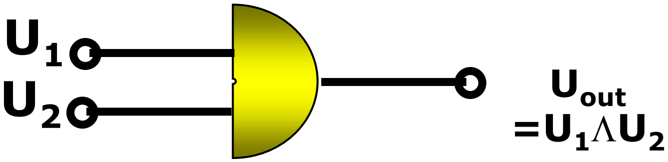


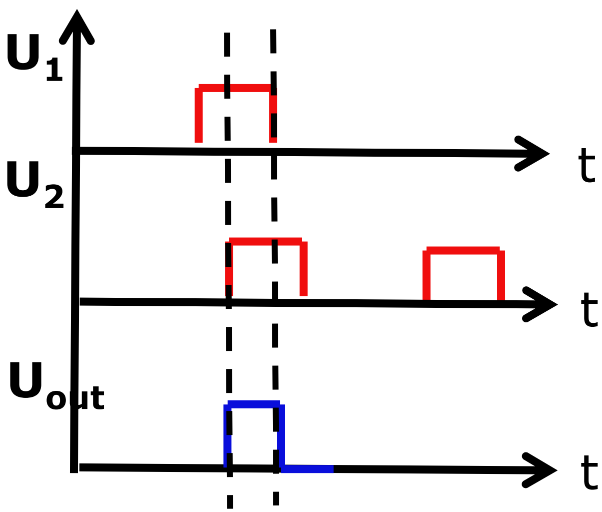


Anti-Coincidence

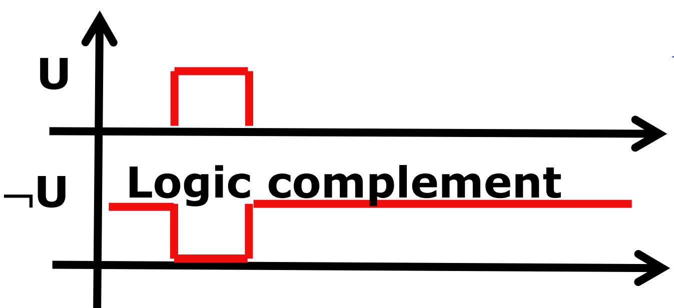
Digital TTL Logic Modules

AND Overlap Coincidence



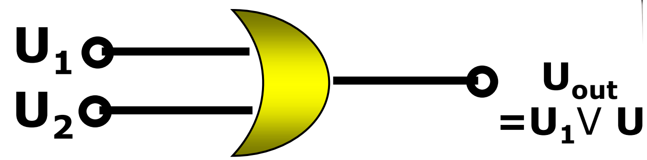


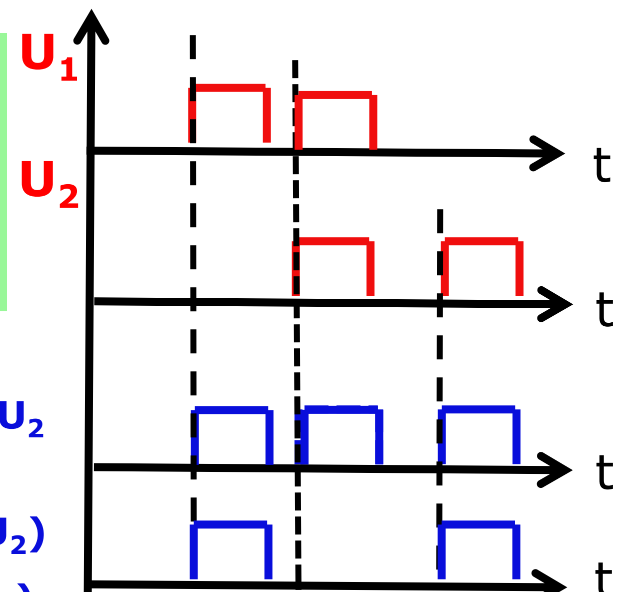
For fast timing: use fast negative logic



OR (inclusive)

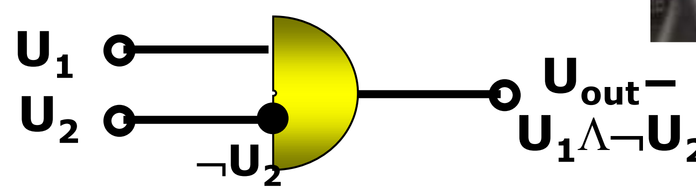
1-3 Co/Anticoincidence logic unit (TTL)





incl $U_1 \vee U_2$

ex $(U_1 \vee U_2)$
$\wedge\neg(U_2 \wedge U_1)$

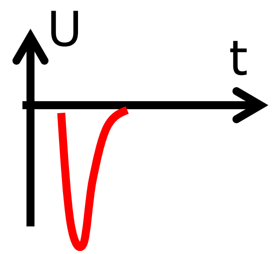


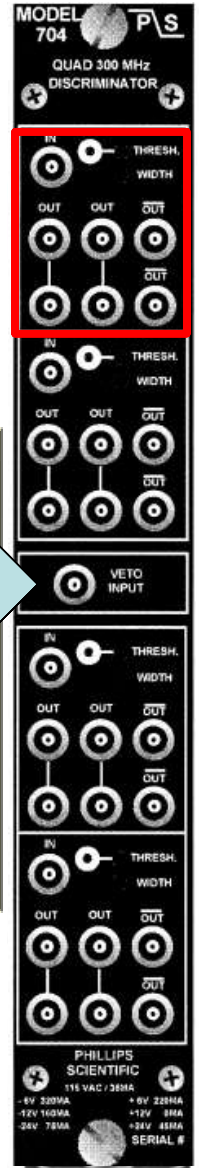
Anti-Coincidence

Logic Chain Elements: Fast NIM Modules

Fast LE Discriminator

Pre/Amp





Input: fast, narrow NIM signal

Veto

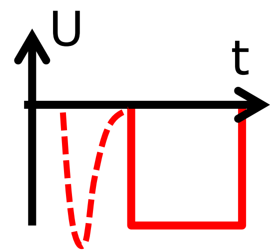
NIM = current based logic, with negative "true"

I = -16 mA

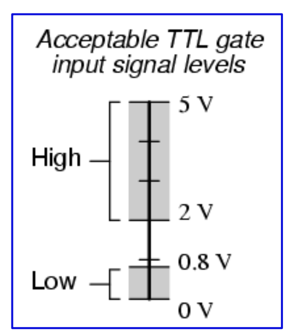
@ 50 Ω → - 0.8 V

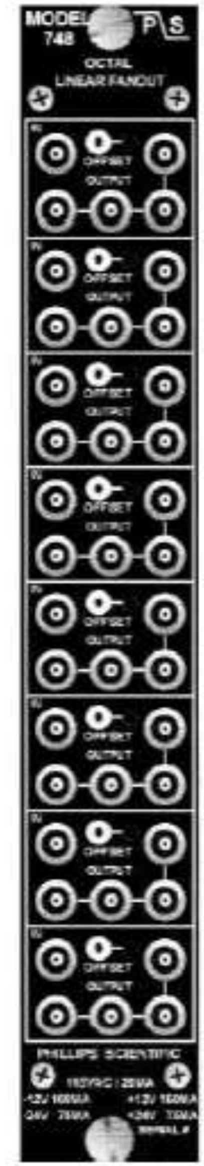
Check on 50 Ω termination

Gate & Delay Generator



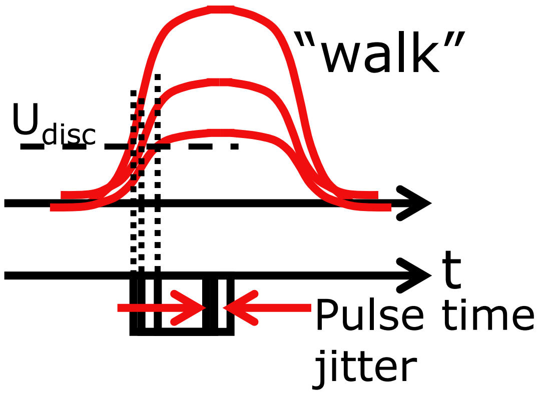
Output: Long NIM/TTL "gate" signal





Fan In/ Fan Out Module

Overlap Coincidence/Coincidence Resolution



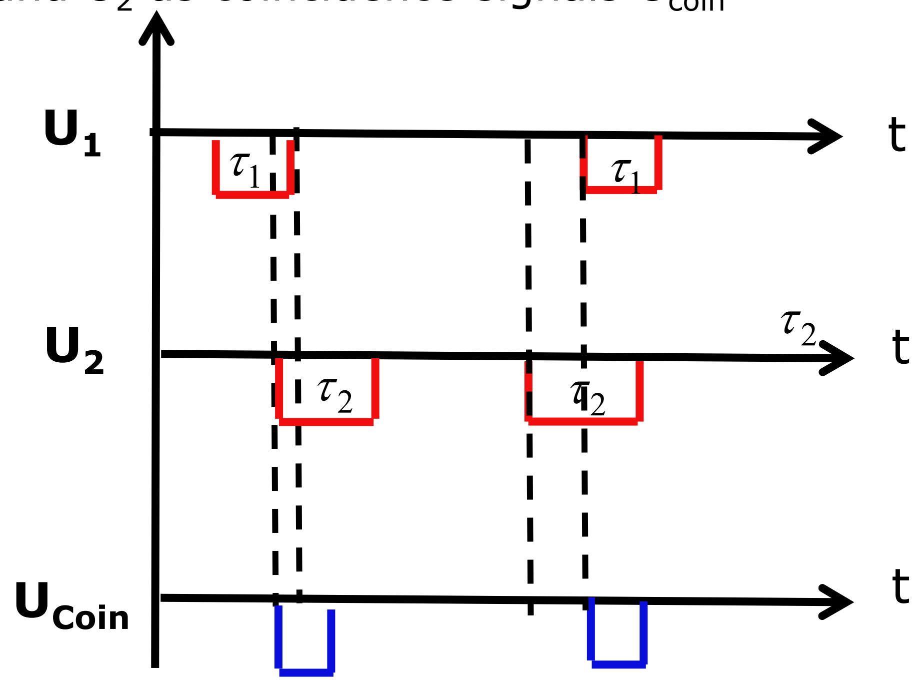
2 physically simultaneous events are detected in 2 counters at different times → time jitter.

Electronic coincidence resolution time = minimum time of signal overlap.

Typical Co resolution time: $\Delta T = \tau_1 + \tau_2$

Detection of an event in detector is a stochastic process → statistical distribution both in pulse amplitude and risetime → time variation in crossing a discriminator threshold level. >>> Additional systematic "walk".

Detection of 2 instances of correlated signals U_1 and U_2 as coincidence signals U_{coin}



Digital Event Data Structure

Example of event stream with signals (observables) measured simultaneously in 3 inputs of the Data Acquisition Module (DDC-8),
>>>>> trigger signal: inclusive OR (det1 V det2)
Sample below displays 6 successive events, 1 of them is a "coincidence."

Single event "Det 1"

Single event "Det 2"

Event#	Input 0 Channel #	Input 1 Channel #
51	1542	0
52	1530	0
53	1486	0
54	1789	256
55	1547	0
56	1533	0

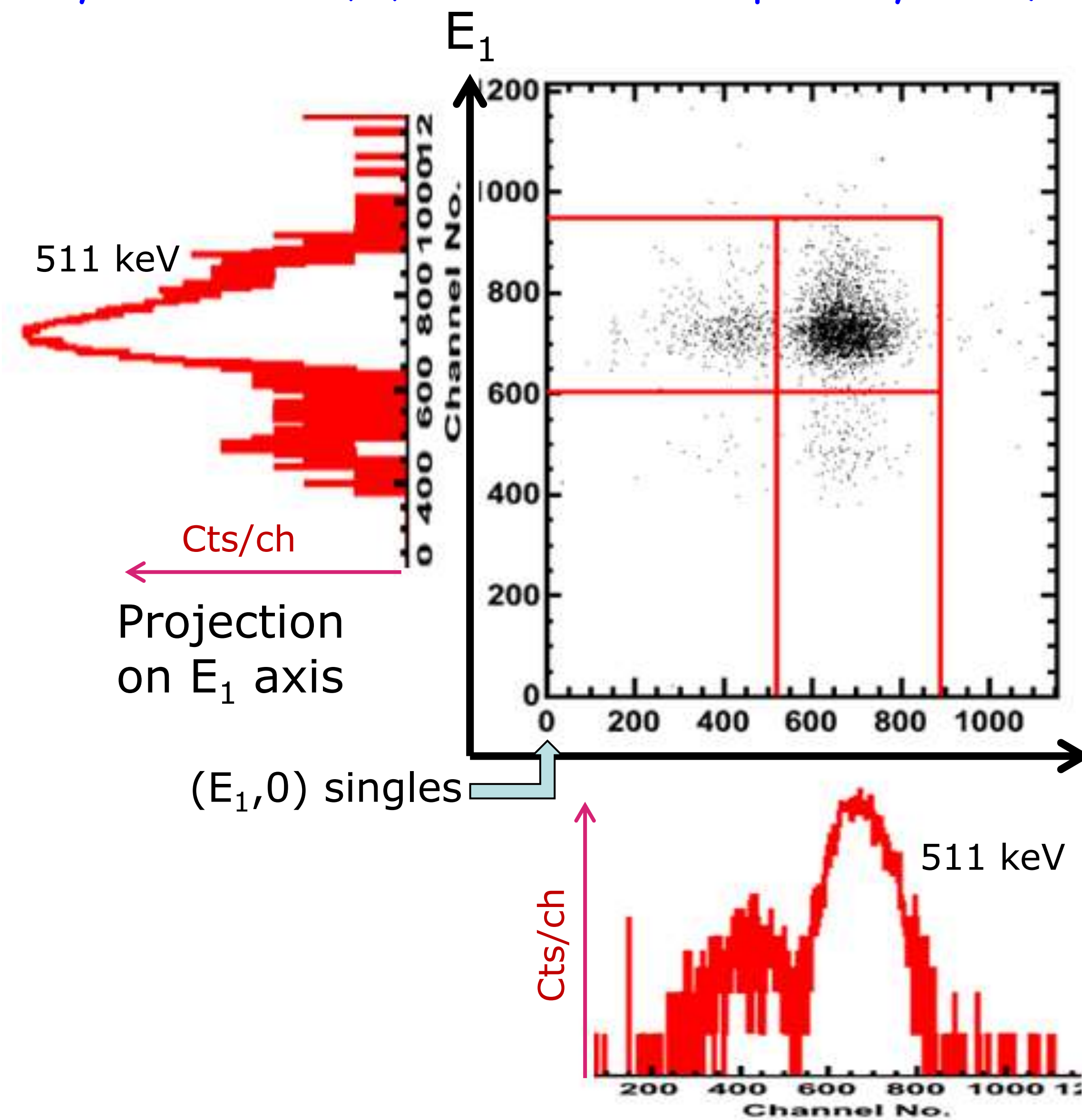
Coincident event 0 .AND. 2

Coincident event 0 .AND. 1

With OR trigger, coincidence "resolution" is given by slow DAQ electronics.
Fast front-end determination reduces random background.

2D Parameter Coincidence Data

Only coincident γ–γ events are accepted by DAQ.



2D Scatter Plot:

Each point represents one 2D event $\{E_1, E_2\}$

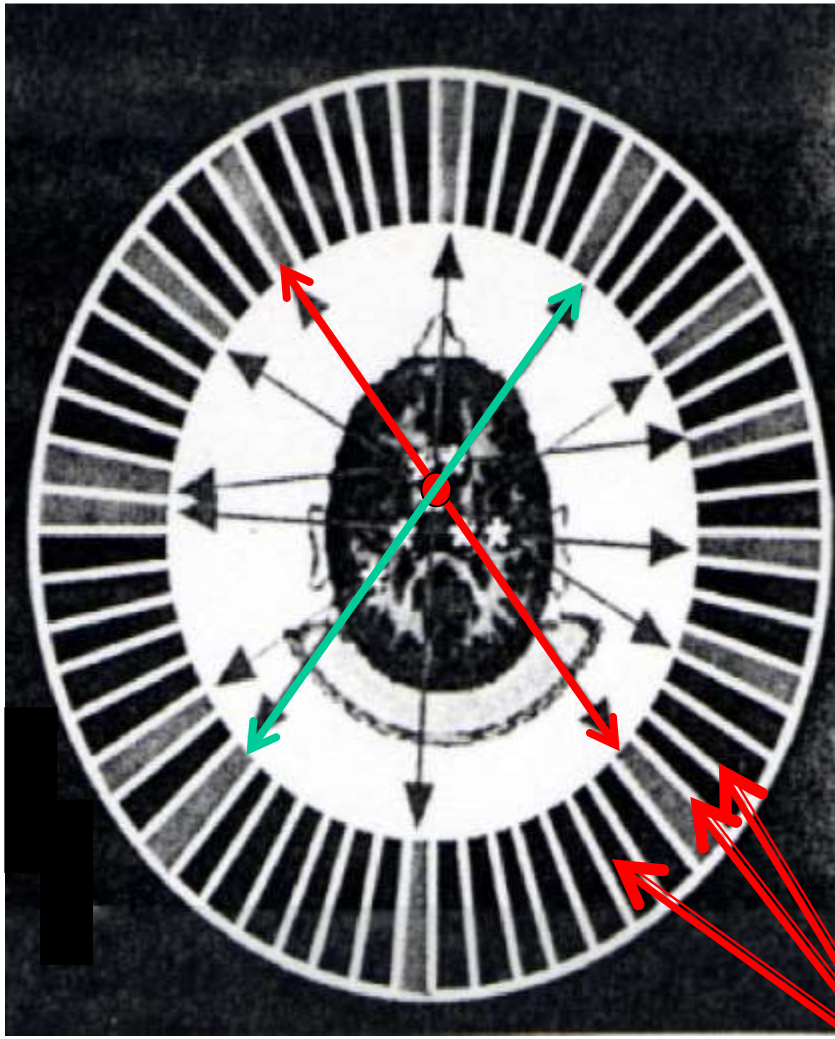
"Minimum Bias" → Multiplicity=2

(0, E_2) singles

Projection on E_2 axis

Radiation Detectors for Medical Imaging

Positron emission tomographic (PET) virtual slice through patient's brain



Administer to patient labeled tracers, e.g.,
radioactive water: $H_2{}^{17}O$
radioactive acetate: $^{11}CH_3COOX$

Observe ^{17}O or ^{11}C β^+ decay mostly via β^+ annihilation

$$e^+ + e^- \rightarrow 2\gamma(511\ keV)$$

Positron e^+ (anti-matter) annihilates with electron e^- (its matter equivalent of the same mass) to produce pure energy (photons, γ-rays). Energy and momentum balance require back-to-back (180^0) emission of 2 γ-rays of equal energy

γ Detectors (e.g., NaI(*Tl*),…)