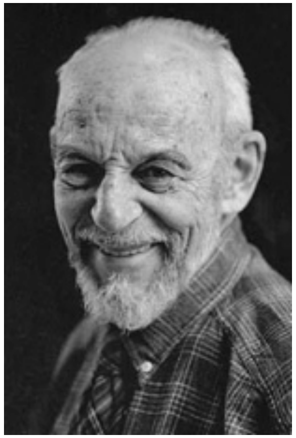
Positronium Decay and Correlated Photons

804

Thursday May 15, 2014

Outline

- A little about radioactivity
- A little about the atomic physics of positronium
  - M. Deutsch Phys Rev **82** 455 (1951),**83** 866 (1952),**84** 601 (1952), **85** 1047 (1952)
- Positronium two and three photon decay
  - The positronium correlated two photon state and polarization
  - Change of photon basis states
- The parity of Positronium in the ground state
- Demonstration of Positronium annhilation and photon correlations
  - Modified Wu & Shaknov experiment Phys Rev **77** 136 (1950)
- Einstein Podolsky Rosen (non)paradox
  - A. Einstein, B. Podolsky, N.Rosen Phys Rev **47** 777 (1935)
  - N. Bohr Phys Rev **48** 696 (1935)
- Why Junior Physics Lab



Martin Deutsch

Radioactivity Primer

- Definition: Curie = 3.7×10^{10} decays/sec
  - The Na_{22} source in experiment 1×10^{-4} C: γ 2, 0.5 Mev → 1×10^{-6} watts
- Definition: Roentgen Equivalent Man REM = 10^{-2} Joules(absorbed)/kg = 10^{-2} Sieverts Eq Man
- Background at sea level: 2×10^{-5} REM/hr --> 5×10^{-4} REM one day of exposure
- Background in jet plane at 30kft: 5×10^{-4} REM/hr
- Dose from chest X-ray: 10^{-2} REM

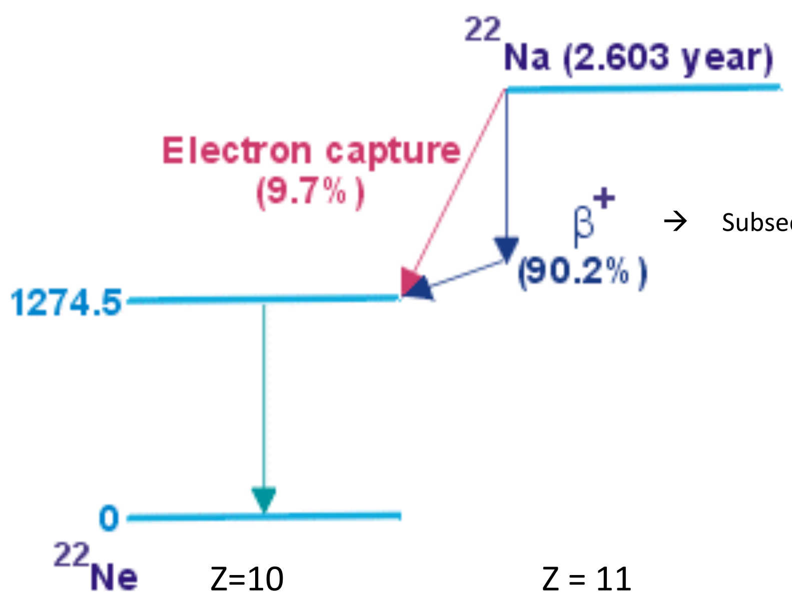
Allowed dose in a year REM

Whole body	5
extremities	50
eye	15
Baby whole body	0.5

Full body dose from unshielded Na_{22} source at 2 meters ~ 1×10^{-4} REM/hr
Full body dose with lead shielding is indistinguishable from background

Na_{22} production and decay scheme

Production: Bombard magnesium with 66MeV Protons for days at 100 microamps. Converts proton to neutron and emission of positron. Then, chemistry to separate sodium from other elements and time to allow for decay of short lived nuclei.



→ Subsequent decay of Positronium 2 x 0.51Mev gammas

Positronium and Hydrogen energy levels

Electron –e m_e s = ½ $\mu = \mu_0$
Proton +e $1836m_e$ I = ½ $\mu = 1.519\text{x}10^{-3}\mu_0$

$a_0 = \frac{h^2}{(2\pi e)^2 m'}$ $E_{n=1} = -\frac{(2\pi)^2}{2}\frac{e^4 m'}{h^2}$ $m' = \frac{m_1 m_2}{m_1 + m_2}$

Electron -e m_e s = 1/2 $\mu = \mu_0$
Positron +e m_e s = 1/2 $\mu = \mu_0$

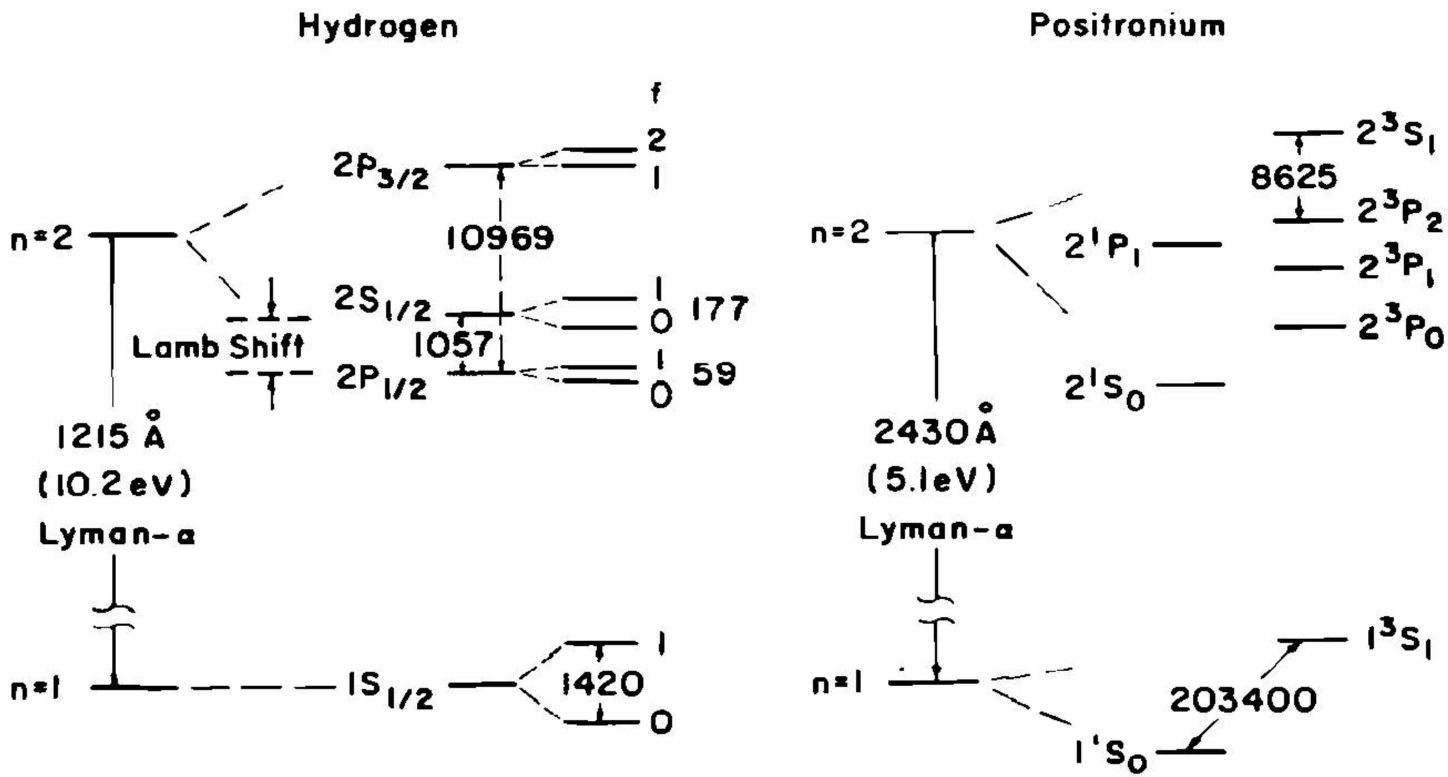


Figure 1 Schematic comparison of the $n = 1$ and the $n = 2$ energy levels of hydrogen and positronium. Energy level differences are given in MHz to the nearest MHz; for the exact experimental and theoretical values see Drell (1979) for hydrogen, and consult the text for positronium.

S,Berko ,H.Pendelton Ann Rev Nucl Part Sci **30** 543 (1980)

Positronium decay

- S=0 state decays from s state: two photons

$$\Gamma^{(0)}_{2\gamma}(n^1S_0) = \sigma v\left|\Psi_n(0)^2\right| = \frac{\pi mc^2\alpha^5}{hn^3} = 8x10^9 \,/\sec\ (n=1) \quad \alpha = \frac{2\pi e^2}{hc} \approx \frac{1}{137}$$

- S=1 state decays from s state: three photons

$$\Gamma^{(0)}_{3\gamma}(n^3S_1) = \frac{4}{9}(\pi^2 - 9)\frac{\pi mc^2\alpha^6}{hn^3} = 7x10^6 \,/\sec\ \ (n=1)$$

- The two photon state of positronium
  – Zero momentum, angular momentum, rest mass
  – Only possibility back to back equal energy photons with total angular momentum zero

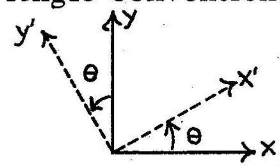
$$|\Psi^{n=1}_{2\gamma}> = \frac{1}{\sqrt{2}}|RR> \pm \frac{1}{\sqrt{2}}|LL>$$

Polarization algebra

Need to express two photon states RR> and LL> in linear polarization x and y basis rather than circular polarization basis to couple to demonstration.

Table 1: Probability amplitudes for photon polarization states

Angle convention: (Beam emerges toward reader.)



FROM STATE

TO STATE

	$\|x\rangle$	$\|y\rangle$	$\|x'\rangle$	$\|y'\rangle$	$\|R\rangle$	$\|L\rangle$
$\langle x\|$	1	0	$\cos\theta$	$-\sin\theta$	$-i/\sqrt{2}$	$i/\sqrt{2}$
$\langle y\|$	0	1	$\sin\theta$	$\cos\theta$	$1/\sqrt{2}$	$1/\sqrt{2}$
$\langle x'\|$	$\cos\theta$	$\sin\theta$	1	0	$\frac{1}{\sqrt{2}}e^{i(\theta-\frac{\pi}{2})}$	$\frac{1}{\sqrt{2}}e^{-i(\theta-\frac{\pi}{2})}$
$\langle y'\|$	$-\sin\theta$	$\cos\theta$	0	1	$\frac{1}{\sqrt{2}}e^{i\theta}$	$\frac{1}{\sqrt{2}}e^{-i\theta}$
$\langle R\|$	$i/\sqrt{2}$	$1/\sqrt{2}$	$\frac{1}{\sqrt{2}}e^{-i(\theta-\frac{\pi}{2})}$	$\frac{1}{\sqrt{2}}e^{-i\theta}$	1	0
$\langle L\|$	$-i/\sqrt{2}$	$1/\sqrt{2}$	$\frac{1}{\sqrt{2}}e^{i(\theta-\frac{\pi}{2})}$	$\frac{1}{\sqrt{2}}e^{i\theta}$	0	1

MIT 804 Kerman, Sartori

Change of Basis

$$\begin{pmatrix} \langle xx|\Psi\rangle \\ \langle xy|\Psi\rangle \\ \langle yx|\Psi\rangle \\ \langle yy|\Psi\rangle \end{pmatrix} = \overbrace{\begin{pmatrix} \langle xx|RR\rangle & \langle xx|RL\rangle & \langle xx|LR\rangle & \langle xx|LL\rangle \\ \langle xy|RR\rangle & \langle xy|RL\rangle & \langle xy|LR\rangle & \langle xy|LL\rangle \\ \langle yx|RR\rangle & \langle yx|RL\rangle & \langle yx|LR\rangle & \langle yx|LL\rangle \\ \langle yy|RR\rangle & \langle yy|RL\rangle & \langle yy|LR\rangle & \langle yy|LL\rangle \end{pmatrix}}^{U} \begin{pmatrix} \langle RR|\Psi\rangle \\ \langle RL|\Psi\rangle \\ \langle LR|\Psi\rangle \\ \langle LL|\Psi\rangle \end{pmatrix}$$

Example matrix element :
assumes independent operations on the two photons

$$\langle xy|RL\rangle = \langle x|R\rangle\langle y|L\rangle$$

$$U = \frac{1}{2}\begin{pmatrix} -1 & 1 & 1 & -1 \\ -i & -i & i & i \\ -i & i & -i & i \\ 1 & 1 & 1 & 1 \end{pmatrix}$$

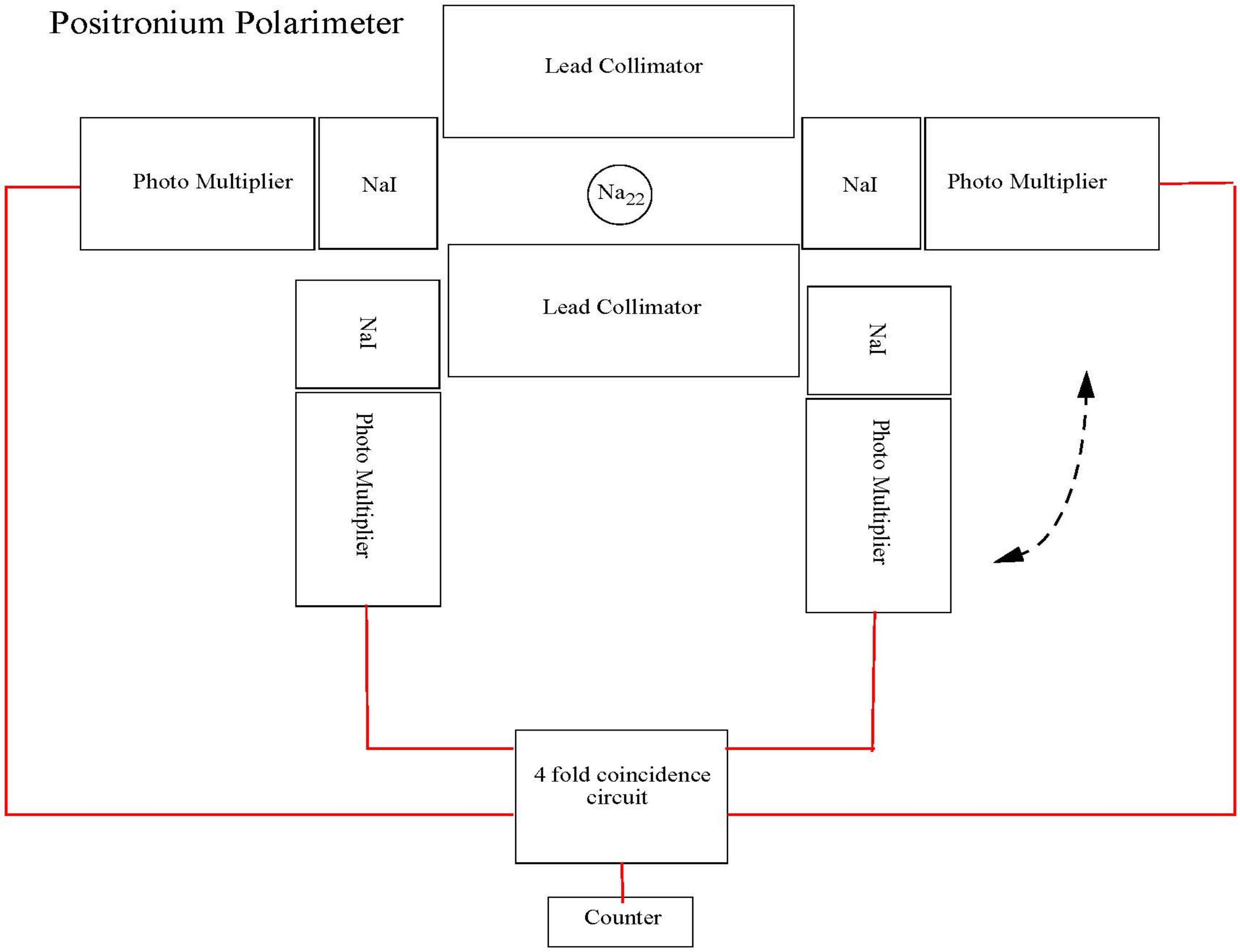
$$\begin{pmatrix} -1/\sqrt{2} \\ 0 \\ 0 \\ 1/\sqrt{2} \end{pmatrix} = U \begin{pmatrix} 1/\sqrt{2} \\ 0 \\ 0 \\ 1/\sqrt{2} \end{pmatrix}$$

even parity

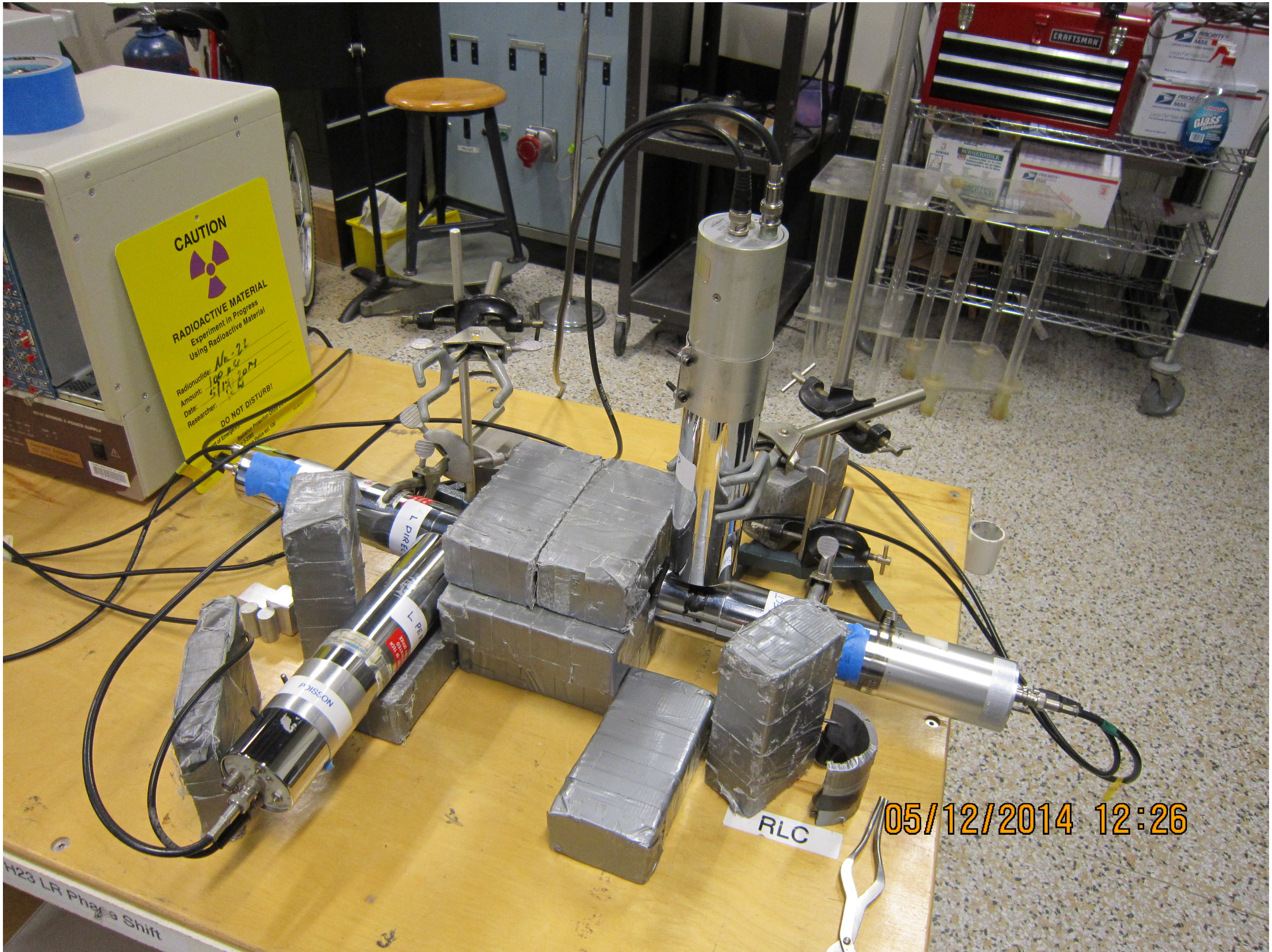
$$\begin{pmatrix} 0 \\ -i/\sqrt{2} \\ -i/\sqrt{2} \\ 0 \end{pmatrix} = U \begin{pmatrix} 1/\sqrt{2} \\ 0 \\ 0 \\ -1/\sqrt{2} \end{pmatrix}$$

odd parity

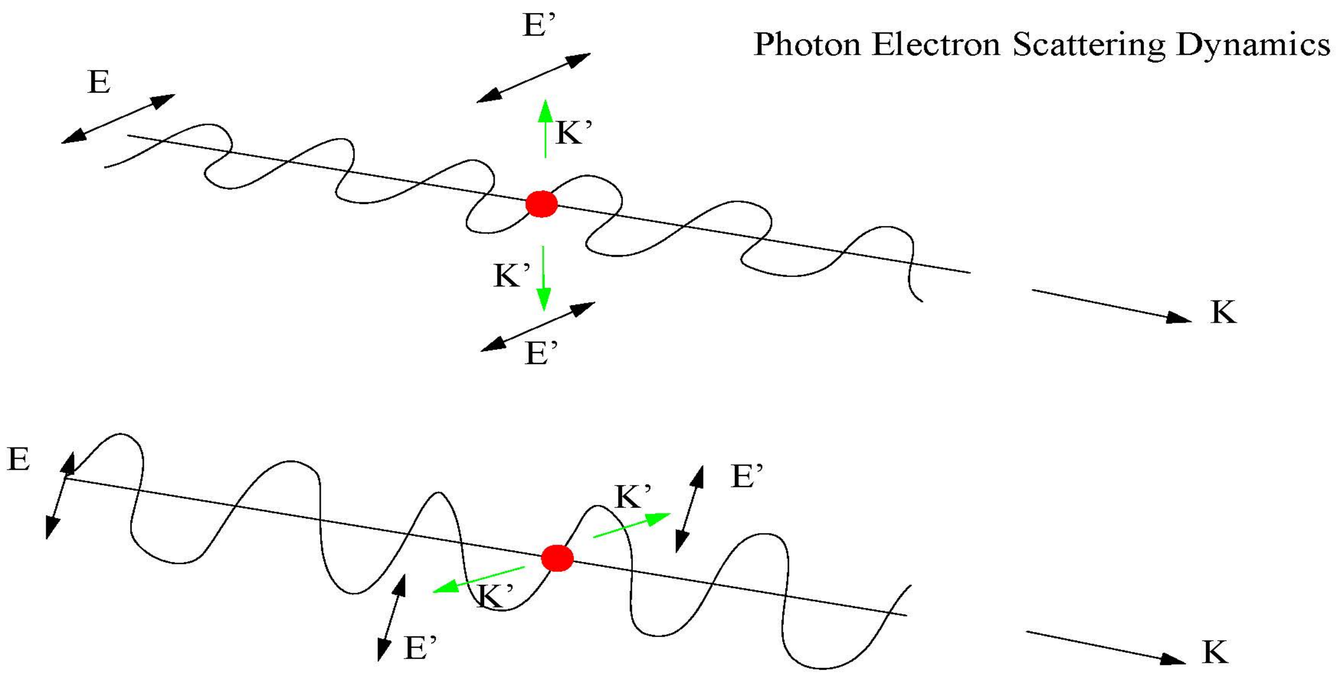
Positronium Polarimeter



Polarimeter

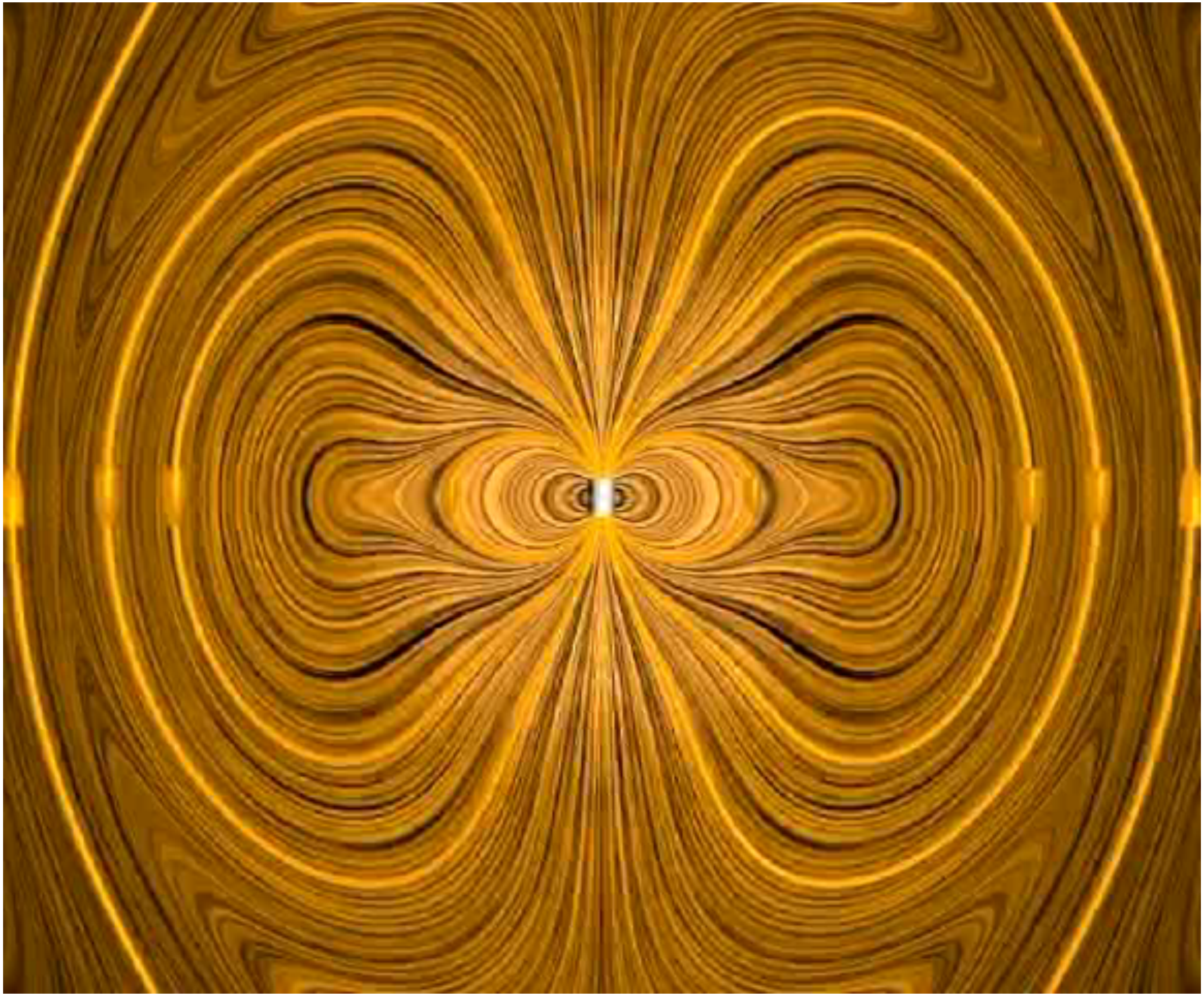


Photon electron scattering dynamics



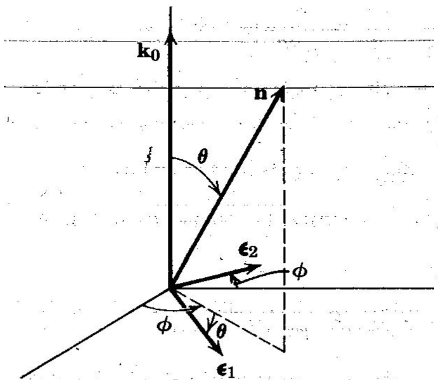
$$\sigma_{Thomson} = \frac{8\pi}{3}\left(\frac{e^2}{mc^2}\right)^2 = 6.65 \mathrm{x} 10^{-25}\,\mathrm{cm}^2 \qquad \frac{d\sigma}{d\Omega} = \left(\frac{e^2}{mc^2}\right)^2 \left|\varepsilon_{scat} \bullet \varepsilon_{inc}\right|^2$$

Electric dipole radiation



John Belcher

Photon – electron scattering : Compton scattering cross section and angular distribution



$$\frac{E_{scat}}{E_{inc}} = \frac{1}{1+\frac{E_{inc}}{mc^2}(1-\cos\theta)}$$

Compton scattering

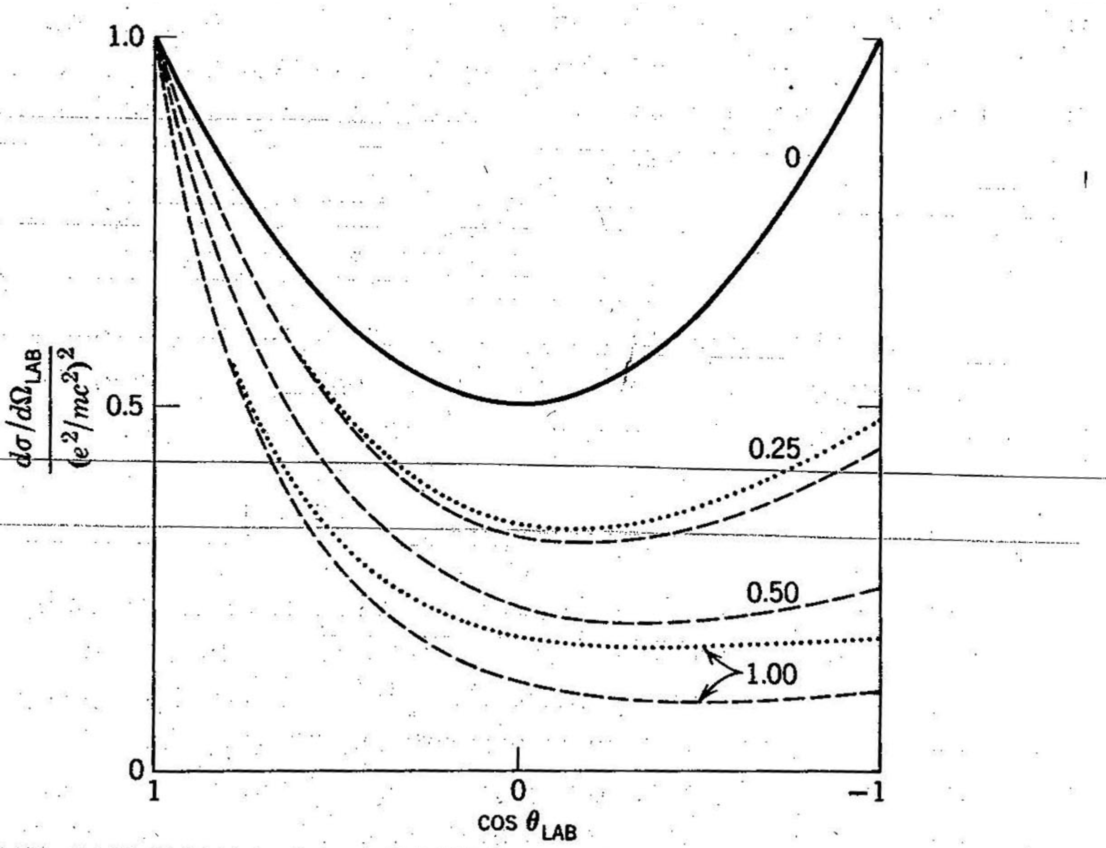
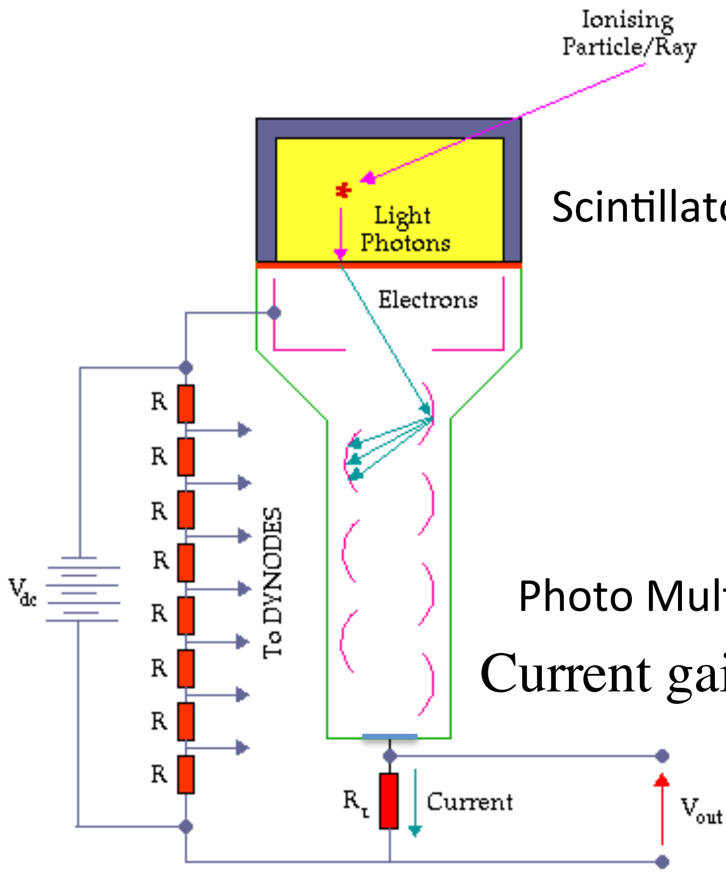


Fig. 14.13 Differential scattering cross section of unpolarized radiation by a point charged particle initially at rest in the laboratory. The solid curve is the classical Thomson result. The dashed curves are the quantum-mechanical results for a spinless particle, with the numbers giving the values of $\hbar\omega/mc^2$. For $\hbar\omega/mc^2 = 0.25$, 1.0 the dotted curves show the results for spin $\frac{1}{2}$ point particles (electrons).

Jackson Classical Electrodynamics

Gamma ray detector



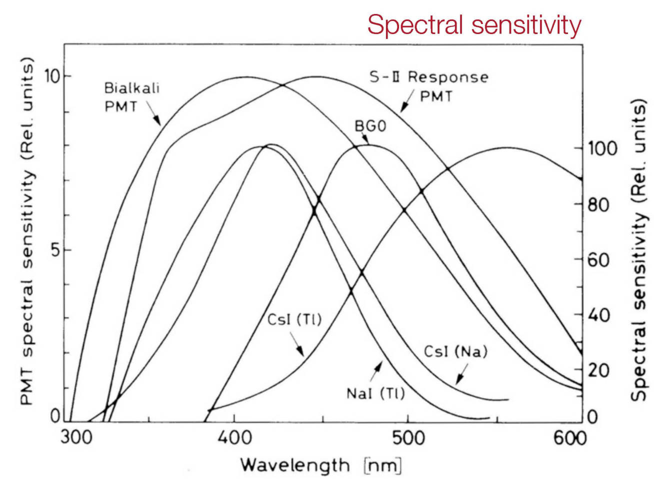
Scintillator NaI

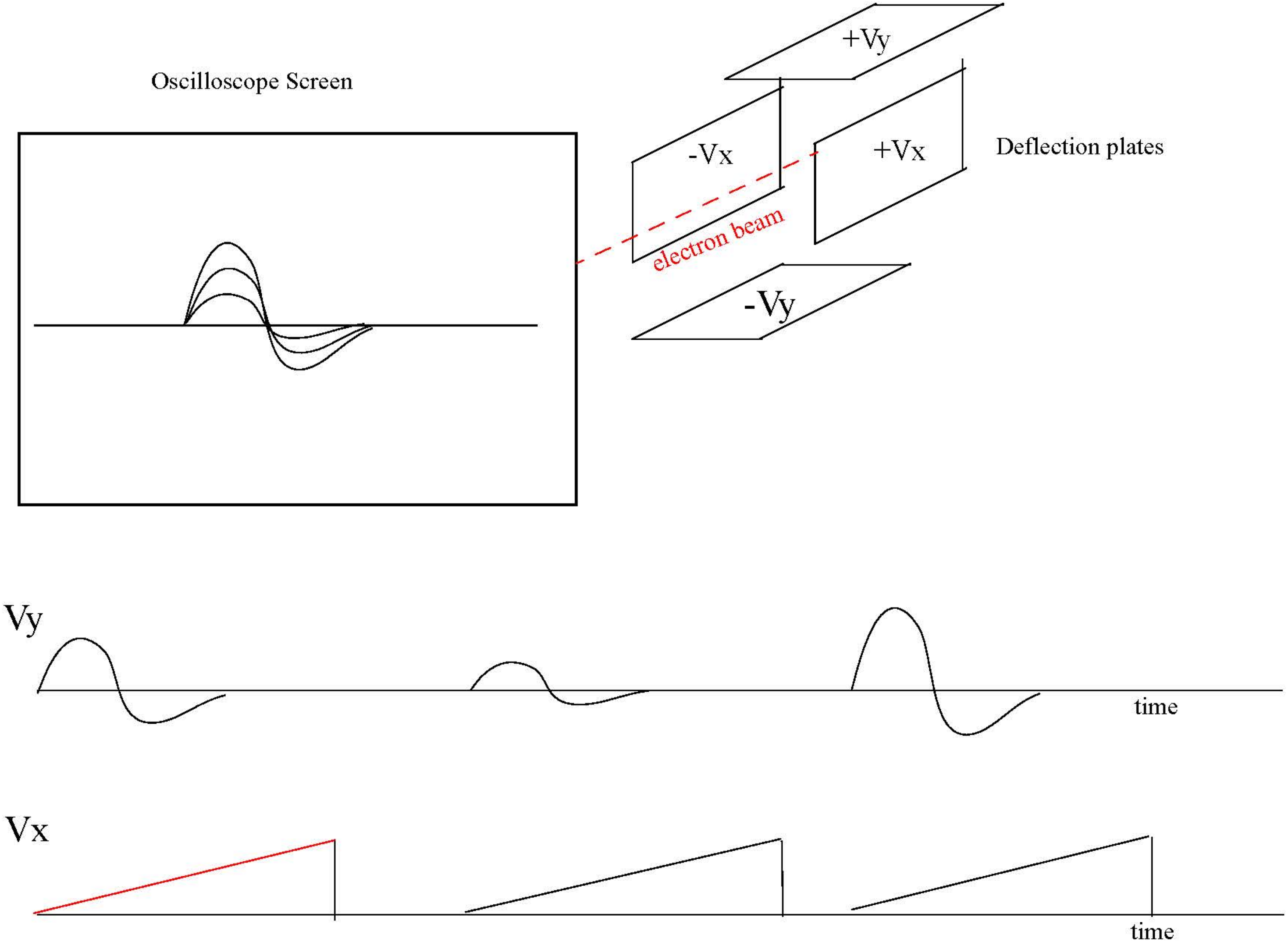
Photo Multiplier

$$\text{Current gain} \sim 3^N \sim 10^6 \qquad N = 12$$

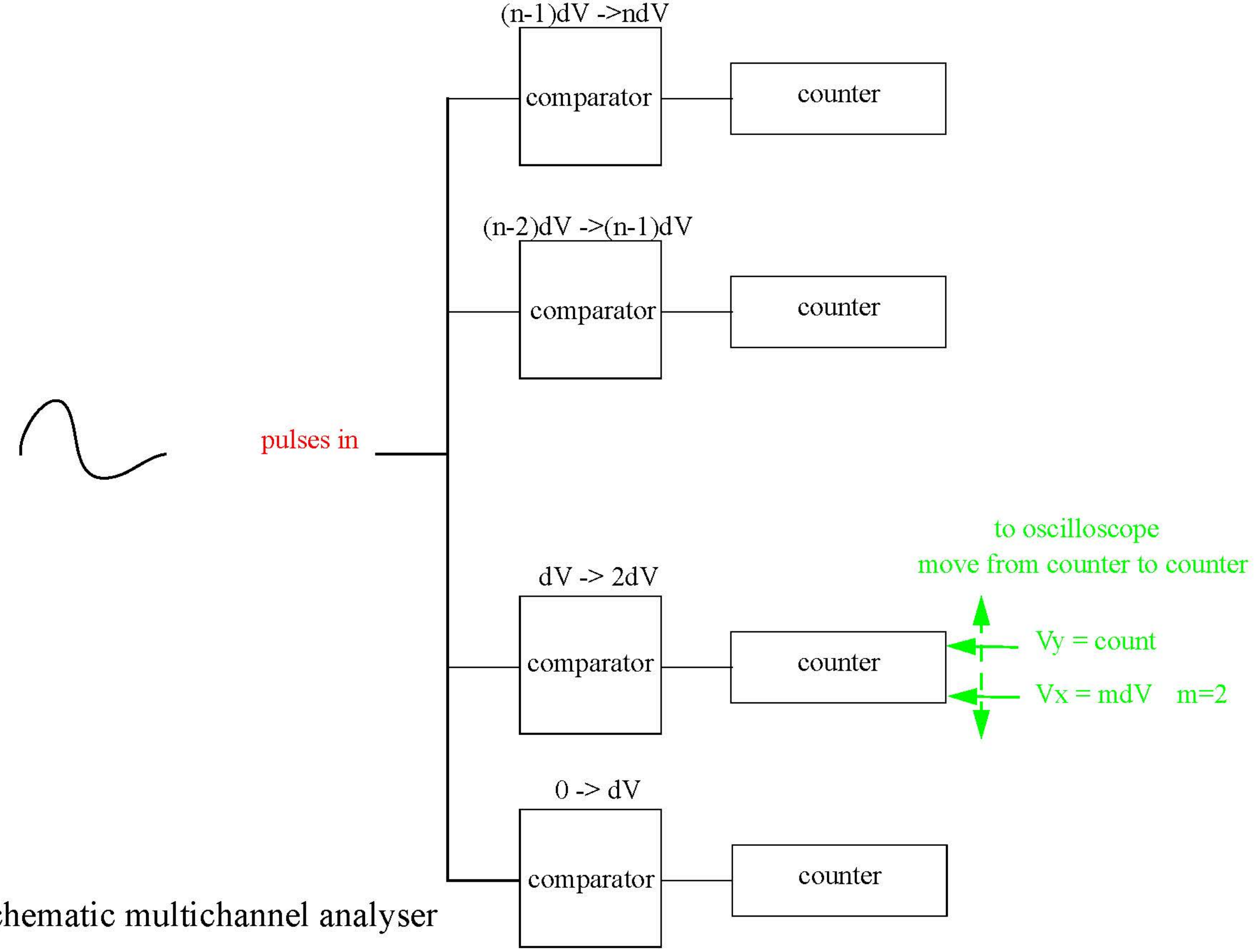
Negative pulses out

Inorganic Crystals – Light Output & PMT Sensitivity



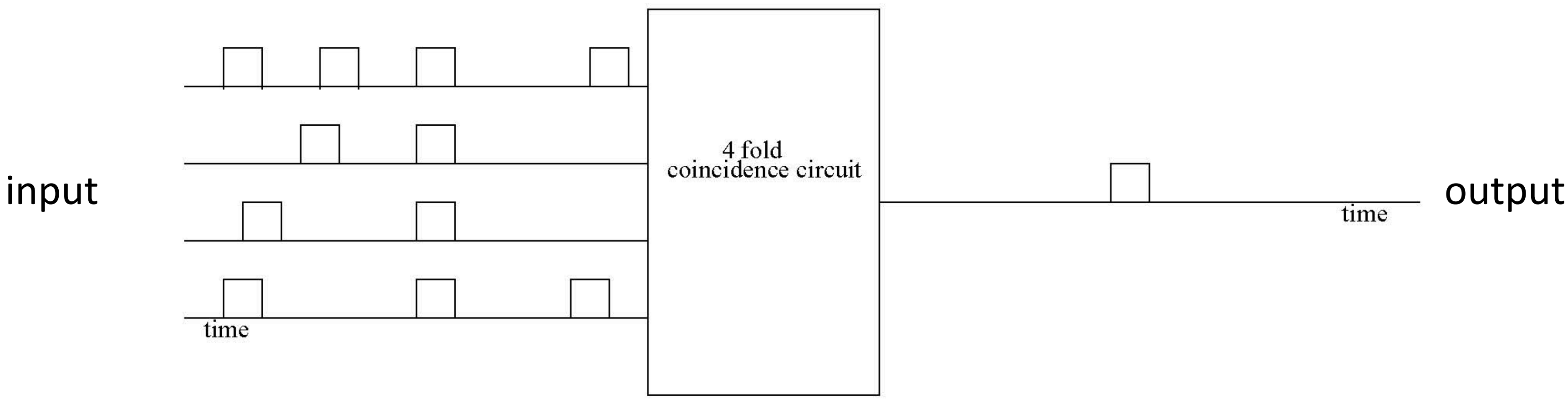


Schematic of an Oscilloscope



Schematic multichannel analyser

Coincidence circuit schematic



Time resolution is 2 * width of pulse

Electronics

Junior Physics Laboratory Experiments

8.13 (Fall/Spring)

Introductory Experiments

I. Photoelectric Effect
II. Poisson Statistics
III. Michelson Interferometer

Regular Experiments

1. Compton Scattering
7. The Franck-Hertz Experiment
9. Relativistic Dynamics
12. Pulsed NMR: Spin Echoes
14. The Speed and Mean Life of Cosmic-Ray Muons
15. Rutherford Scattering
17. Optical Emission Spectra of Hydrogenic Atoms
43. Johnson Noise and Shot Noise
46. 21-cm Radio Astrophysics
51. Optical Trapping

8.14 (Spring)

Regular Experiments

6. The Zeeman Effect
11. Optical Pumping of Rb Vapor
12. Pulsed NMR: Spin Echoes
13. Mössbauer Spectroscopy
39. Superconductivity
46. 21-cm Radio Astrophysics
48. Doppler-Free Laser Spectroscopy
49. Quantum Information Processing
51. Optical Trapping

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