SECTION 1

PROPERTIES OF NUCLEAR RADIATION

Nuclear radiation is emitted by nuclei undergoing certain nuclear and/or electromagnetic transformations. Radioactive isotopes in the process of decaying to stable isotopes are used as sources for such radiations. Table 1, summarizes some of the properties of these radiations.

Type of Particles	Symbol	Relative Charge	Approx. rest mass (relative)	Some sources emitting these Radiations
Neutron	n	o	1	Am - Re Pu - Be
Alpha particle	α	2	4	Am^{241} , U^{238}
Electron, Beta particle	e^-, β^-	-1	1/1840	C^{14} , Sr^{90}
Positron	β^+	+1	1/1840	Na^{22}
Gamma-Ray	γ	No	No	Cs^{137}, Co^{60}
X-Ray	X	No	No	X-Ray units Fe^{57}

Table 1

Alpha-Particles

Alpha-particles are Helium-(He) nuclei composed of two neutrons and two protons. They are emitted by natural radioactive materials such as Uranium, or by certain radioactive isotopes such as Americium- Am^{241}. Alpha-particles have discrete and well-defined energies characterizing the isotope. Alpha-particles lose their energy in matter, by excitation and ionization of the atoms with which they collide. The rate of ionization (or energy loss) is proportional to the mass of the particle. Thus, for a given total energy, the alpha-particles' loss of energy, per length of ionization path, is much greater than the respective loss of energy by electrons. A very small thickness of material, for example, 25 u of aluminium, will completely stop a 5 MeV alpha-particle.

Beta-Particles

Beta-particles are fast electrons emitted by certain decaying nuclei. When a neutron

is transformed into a proton, a beta and an uncharged particle called neutrino are emitted. The beta-decay is usually accompanied by the emission of gamma-rays as is the case of Cs^{137}. Its energy spectrum is continuous from zero to a certain maximum energy E_m depending on the source. Beta-particles lose their energy in matter due to scattering, excitation, ionization and Bremsstrahlung effect (deceleration of electrons in the nuclear field while emitting electromagnetic radiation).

X-Rays and Gamma-Rays

X-rays and gamma-rays are electromagnetic radiations of very high frequency. Gamma-rays are produced by nuclear interactions or by the decay of radioactive isotopes. X-rays are produced by the excitation or removal of orbital electrons and the subsequent filling of the empty levels by other electrons.

X-rays and gamma-rays can be described as particles called photons, with energy E_p, given by the formula:

$$E_p = h\nu = \frac{hc}{\lambda} \quad \text{where}$$

h = Planck's constant = 6.6×10^{-34} joule second

c = the velocity of light in vacuum = 3×10^{8} meters per second

ν = the frequency

λ = the wave length

The interaction of gamma-rays with matter is described by three main effects: The Photoelectric Effect, the Compton Effect and the Pair Production Effect. (These effects are discussed in detail on pages 12 to 15).

Neutrons

The neutron is an uncharged particle which is not affected by electromagnetic fields. Thus neutrons interact with the nuclei of an absorber and are either scattered or absorbed by them. If the neutrons are elastically scattered, the scattering nucleus will gain energy, while if they are absorbed, the absorbing nucleus will become excited and emit other forms of radiation.

Neutrons may be divided into two general groups:

1) Fast neutrons with energy greater than approximately 1 KeV.

2) Slow neutrons with energy less than approximately 1 KeV.

Radioactivity

Natural radioactive elements in the process of decaying will emit alpha, beta, and/or gamma-particles. For example, Am^{241} emits alpha-particles and gamma-rays, while C^{14} emits beta-particles. In addition to naturally radioactive materials, there are those which become radioactive after appropriate nuclear reactions; for example Co^{59} (n,γ) Co^{60}. A third type of radioactive materials are those which result from the fission of Uranium, for example Cs^{137}.

All radioactive elements decay to other elements by emission of particles. The radioactive material is called the "parent" P, and the element to which it decays is called the "daughter", D. The decay from "P" to "D" occurs at a rate which varies according to the element. The number of P atoms decreases while the number of D atoms increases.

The number of P atoms remaining at any time t is:

$$N = No\, e^{-\lambda t} \qquad (1)$$

where:

No = Number of P atoms at the time t, t = o

N = Number of P atoms at the time t, t > o

λ = The decay constant

If the decay constant λ is large, the radioactive atoms of P will decrease rapidly, and in a short time will be expended. If λ is small, then N will decrease slowly and the element will remain radioactive. To compare the rate of decay between sources, we calculate the time T at the point when $\frac{N}{No} = \frac{1}{2}$.

According to this: $\frac{N}{No} = \frac{1}{2} = e^{-\lambda T}$

$$\ln \frac{N}{No} = \ln \frac{1}{2} = -\lambda T$$

$$T = \frac{\ln 2}{\lambda}$$

Thus T is called the "half-life time" and noted as $T_{\frac{1}{2}}$. For example, $T_{\frac{1}{2}}$ of U^{238} : 4.5×10^9 years. $T_{\frac{1}{2}}$ of Ag^{110} : 24 seconds.

The activity of an element is defined as λN. The unit of activity is called Curie, where 1 Curie = 3.7×10^{10} disintegrations per second.

Neutron Activation

When neutrons pass through matter they interact with the atoms of the matter in two ways: by scattering and absorption. These interactions depend strongly on the energy of the neutrons. In the scattering process the neutron loses energy with every collision until it either reaches thermal equilibrium with the material, or passes through it. The neutron having no electric charge, can penetrate the electric field of the nucleus. When the neutron is very close to the nucleus, it is "captured" and a composite nucleus is produced according to the formula :

$$ {}_{z}X^{A} + n_{o}^{1} \longrightarrow \left[{}_{z}X^{A+1} \right] $$

The composite nucleus is in an excited state and soon releases its excess energy by radioactive disintegration. Typical reactions produced by the absorption of a neutron are: (n, γ) ; (n, α) ; (n,p) ;(n, 2n) ; (n, fission).

Theoretically the cross section σ for the absorption of low energy neutrons is inversely proportional to the velocity of the neutron $\sigma \propto \frac{1}{v} \propto \frac{1}{\sqrt{E}}$ where E is the energy of the neutron.

Thus, thermal neutrons have very high absorption cross sections.

Radioisotopes can be produced by irradiating a sample by a flux of thermal neutrons. This process is called "Neutron Activation".

For example, ${}_{47}Ag^{107} + n_{o}^{1} \rightarrow {}_{47}Ag^{108} \xrightarrow[2.3\,min.]{\beta} {}_{48}Cd^{108}$ $\left[\sigma = 48 \times 10^{-24}\ cm^2 = 48\ barn.\right]$

The resulting radioisotope is identified by examining its spectrum and measuring its half-life time.

The quantity of radioactive material produced depends upon:

$\Sigma(\sigma)$: Effective cross section for the nuclear reaction in cm^2. $\left[1\ cm^2 = 10^{-24}\ barn.\right]$

ϕ : Neutron flux in neutrons/cm^2 sec.

a : Abundance of the target isotope expressed as a fraction; (e.g. 15% would be expressed as 0.15).

M : Atomic weight of target element.

W : Weight of element in target in grams.

t : Irradiation time.

t_d : Decay time after activation.

$T_{\frac{1}{2}}$: Half-life time of the isotope produced.

N_o : Avo adro's number.

The activity A in mc is then,

$$A = \frac{N_o \, \Sigma(\sigma) \phi \, aW}{3.7 \times 10^7 M} \left(1 - e^{- \frac{0.693 \, t}{T_{\frac{1}{2}}}} \right) \left(e^{- \frac{0.693 \, t_d}{T_{\frac{1}{2}}}} \right)$$

Most radioactive materials are produced in atomic reactors by this method of neutron activation.

The Mössbauer Effect

e recoilless emission and absorption of gamma quanta by an atomic nucleus (observed by R.L. Mössbauer in 1957), is called the Mössbauer effect. When a free atomic nucleus emits a gamma-quanta, it receives a recoil energy of $E_R = \frac{E^2}{2Mc^2}$, where: Rückstoß

E is the energy of the gamma-quantum; M, the mass of the atom, and c, the velocity of light. This gamma-quantum, emitted by a free nucleus in its excited state, would then have a lower energy (lower by the amount of the recoil energy) than the difference of energies between the excited and the ground states. The same process occurs when a free atom absorbs a gamma-quantum.

Because of the loss of energy due to recoil of both emission and absorption, a gamma-quantum emitted by a free nucleus will not excite another free nucleus of the same isotope, because the gamma-nuclear resonance is very sharp and resonant absorption nnot take place.

If the source or absorber is situated inside a crystal, then, as long as the recoil energy is less than the binding energy between atoms in the crystal, the emitting or absorbing nuclei do not leave their site (Lage) in the crystal. In such a case the recoil momentum is transmitted to the entire lattice (Gitter) as a whole. Part of the nuclear transition energy can be absorbed by the lattice vibration. The energy taken up by the entire lattice is negligible. If the recoil energy for a free nucleus is less than the phonon energy, then it is possible for the nucleus in the crystal to emit or absorb radiation with an energy equal to that of the nuclear transition.

The usefulness of the Mössbauer effect is related to the fact that the linewidth observed is of the order of the natural linewidth of the excited nuclear states.

The probability of recoilless emission or absorption depends strongly on the energy

of the emitted gamma-quantum and on the properties of the lattice in which the emitted nucleus is situated. For a harmonic solid it is given by $\exp(-k < x^2 >_T)$, where k is the wave vector of the gamma-ray, and $< x^2 >_T$ is the mean square displacement, $< >_T$ meaning thermal average. If the Debye model is used to describe the solid, then

$$k^2 < x^2 >_T = 3 \frac{E_R}{k\theta_D} \left[\frac{1}{4} + \left(\frac{T}{\theta_D} \right)^2 \int_0^{\theta/T} \frac{x \, dx}{e^x - 1} \right]$$

where θ_D is called Debye temperature. Thus, if the nuclear transition is of low energy and if the Debye temperature of the crystal is high, then the probability for recoilless emission or absorption is high.

In order to observe the Mössbauer effect a velocity is given to the absorber or the source, and though a Doppler shift of the energy a velocity spectrum can be recorded. In general, only velocities of the order of 1 cm/sec are needed.

The most useful Mössbauer isotope is Fe^{57}. The source consists of Co^{57} which is transformed by K capture into the 136 KeV state of Fe^{57}. After ~ 10^{-8} seconds this level decays with the gamma-emission of 122 KeV to the 14.4 KeV level. This 14.4 KeV level of Fe^{57} is the level used in the Mössbauer effect experiments. After ~ 10^{-7} seconds, the 14.4 KeV level decays through internal conversion or gamma emission of 14.4 KeV to the ground state. The decay scheme of Co^{57} is shown in Fig. 1.

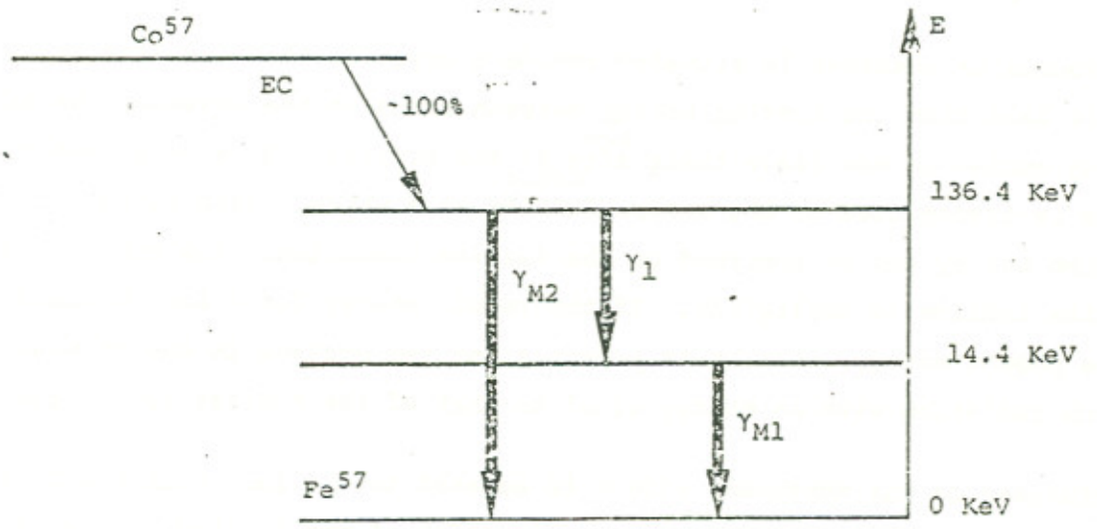

Fig. 1

DECAY SCHEME OF Co^{57}

Generally there are additional effects which determine the form and position of the Mössbauer line, with respect to zero velocity. Such effects are the isomer or chemical shift, the relativistic temperature shift or second order Doppler shift and the quadrupole and the magnetic splittings.

NOTE: When a stainless steel source is used, the resonance line of a stainless steel absorber is at velocity $v=0$. With an iron absorber the resonance is magnetically split into six lines and no resonance occurs at $v = 0$.

SECTION 2

PRINCIPLES OF SCINTILLATION COUNTING

Principles of the Scintillation Counter

The basic process involved in the detection and measurement of ionizing particles is shown in Figs 2 and 3.

An incident particle of energy E_0 impinges on the scintillator where it dissipates its energy in the ionization and excitation of the molecules. A fraction of this energy is converted into N_0 light photons which are radiated in all directions. To maximize the number of photons which fall on the photocathode, the scintillator is surrounded by a reflector. A fraction of these photons cause the emission of T photoelectrons from the photocathode.

These photoelectrons are accelerated towards the first dynode by the potential applied between the photocathode and the first dynode. T photoelectrons strike the first dynode and further electrons are ejected by secondary emission. If, R = 3 to 5, is the average number of secondary electrons per incident electron ejected from the dynode, then RT electrons will impinge on the second dynode.

This electron multiplication process is repeated at subsequent dynodes, each of which is at a higher potential than the preceding one. If there are n dynodes, each with a multiplication factor R, the number of electrons Q_0 finally collected at the anode is R^nT. R^n may vary from 10^5-10^8 depending on the photomultiplier tube.

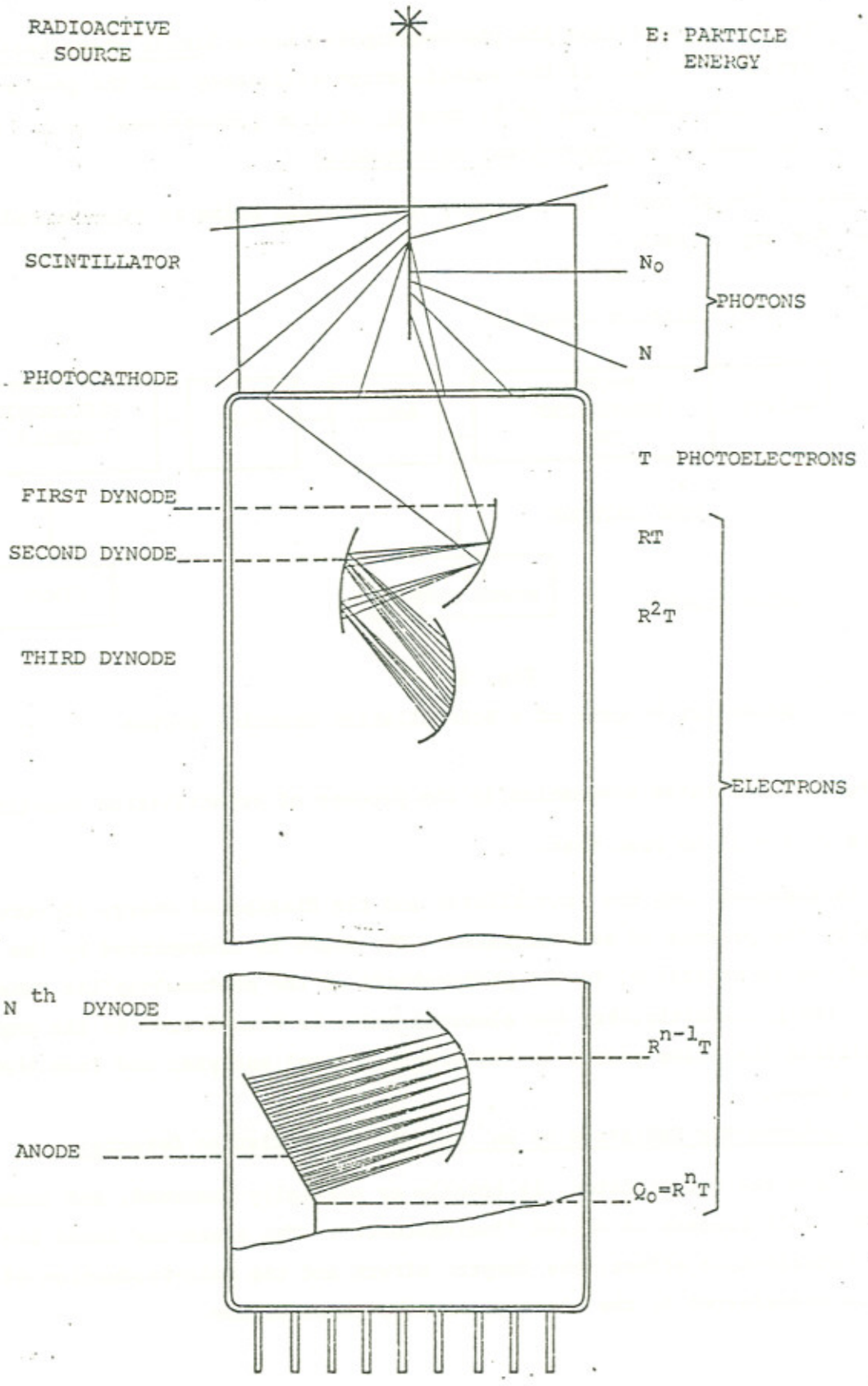

Fig. 2

Photomultiplier Scintillation Counter
Schematic Diagram showing Sequence of Processes

Under normal operating conditions the photomultiplier has a linear characteristic, and Q_o is proportional to N_o. If the scintillation efficiency and the photon collection efficiency are independent of E, then Q_o will be proportional to E_o and the system can be used as a proportional spectrometer.

From the anode of the photomultiplier tube, the electric pulse is transferred to an amplifier for amplification.

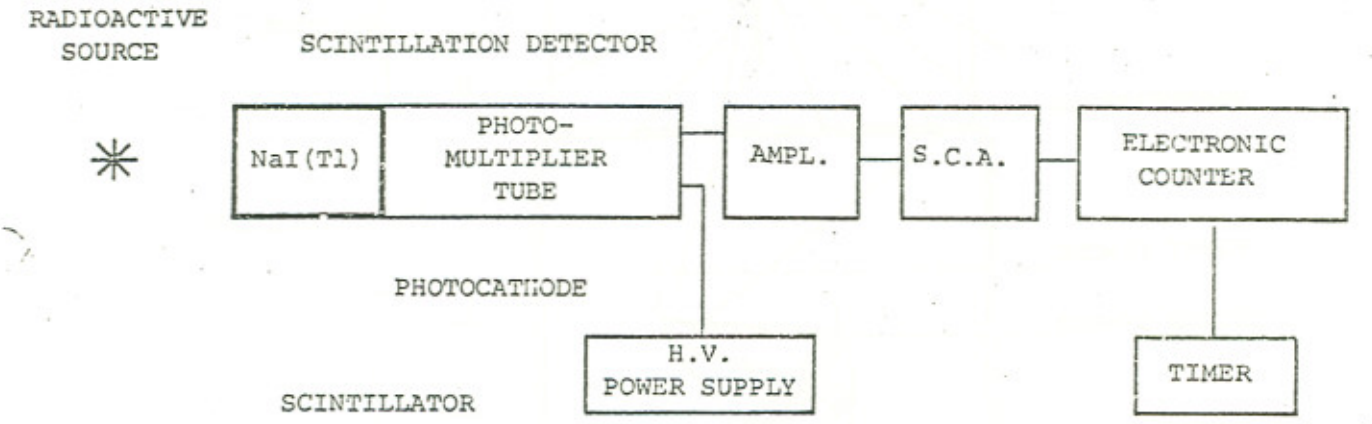

Fig. 3

Schematic Diagram of a Scintillation Counting System

The above figure illustrates schematically the process of scintillation counting.

From Figs 2 & 3 it will be seen that:

A gamma-ray is absorbed into the scintillator and the dissipated energy is converted into photons by the process of scintillation. The light is transmitted by the light reflector and the scintillator, to the photocathode of the photomultiplier tube. From the output of the photomultiplier, the electric pulse is transferred to the amplifier. From the amplifier the pulse passes to the single channel analyzer and from there to the counting system.

Absorption of a Gamma-Ray Radiation by an NaI(Tl) Scintillation Detector

A gamma-ray enters the scintillator, is totally or partially absorbed, and causes scintillation. This process is called "luminescence". The gamma-ray loses its energy through the Photoelectric effect, the Compton effect and the Pair-Production effect. This energy is transferred to the electrons in the scintillator.

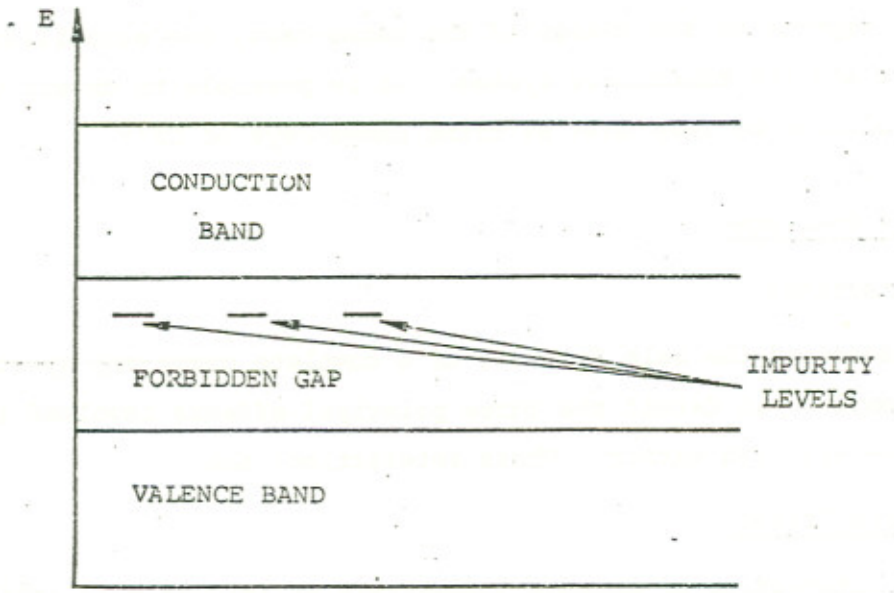

Fig. 4

Band Theory of Solid State Crystals

The internal luminescence process may be explained by the Theory of Bands in solid state physics. The pure crystal is described according to this theory as shown in Fig. 4. In a non-conductive crystal the valence band is full, while the conduction band is empty. The energized electrons excite and ionize the atoms of the scintillator, and thus they excite orbital electrons from the valence band to the conduction band. The electrons return to the valence band by way of emission of light photons in the visible range. Impurities in the crystal will cause additional levels of energy in the forbidden gap, which facilitate the excitation of electrons from the valence band to the conduction band.

The scintillator is transparent to its own scintillations, and therefore the light reaches the photocathode. There is a linear relationship between the energy absorbed in the scintillator, the number of light photons emitted by the scintillator which reach the photocathode, and the pulse height obtained after the photomultiplier. Thus, the pulse height distribution obtained from the photomultiplier is proportional to the gamma-ray energies absorbed in the scintillator.

Auflösung

Resolution: R

The energy resolution R is defined as: $R = \frac{\Delta E}{E} \times 100\%$, where ΔE is the energy spread at the full width of half the maximum height of the photo-peak (FWHM).

The resolution depends on the energy of the gamma-rays, the scintillation crystal, the photomultiplier and the electronic system. It is possible to obtain with NaI(Tl) crystals a resolution of less than 8% using gamma-rays of Cs^{137}

Analysis of the Spectrum

The Basic Interactions

In order to understand the main features of a complete gamma-ray spectrum, it is necessary to consider in detail the three principal effects involved in the interaction of gamma-rays with matter. These interactions are:

a) Photoelectric Effect

The direct interaction of photons (gamma-rays or X-rays) with orbital electrons in an atom, is called the Photo-Electric Effect.
The energy transferred to the ejected photoelectron is:

$$T = E_o - E_b$$

where T is the kinetic energy of the photoelectron, E_o is the energy of the incoming photon, and E_b is the binding energy of the photoelectron ejected. This interaction leaves the original atom with a vacancy in the given shell (K,L,N) and this vacancy when filled gives rise to the characteristic X-ray emission. Since the photoelectric cross section is very high at low energies, the X-rays are absorbed in the detector and the energy is transferred to other photoelectrons. The ultimate result is the transfer of all the X- ray energy to the photoelectrons, which in turn transfer it to optical scintillation photons striking the photocathode. Thus, if this was the only process involved, a gamma-ray source would give a single sharp line on a pulse height analyzer, broadened only by statistical considerations. (See Fig. 5.).

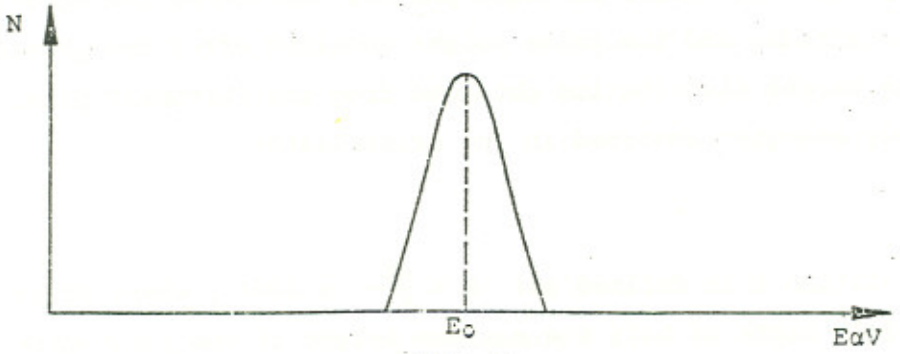

Fig. 5

Distribution due to Photoelectric Effect

b) Compton Effect

The elastic collision between a gamma-ray and a free electron at rest in which part of the gamma-ray energy is transferred to the electron and part remains as a deflected photon is known as the Compton effect. (See Fig. 6).
From the laws of conservation of momentum and energy we arrive at the relations:

$$T = E_o \left\{ 1 + \left[m_o c^2 \Big/ \{ (1 - \cos \theta) E_o \} \right] \right\}^{-1}$$

$$E' = E_o \left\{ 1 + \left[(1 - \cos \theta) E_o / m_o c^2 \right] \right\}^{-1}$$

where E_o is the energy of the incoming photon; E', the energy of the scattered photon; T, the energy given to the electron, $m_o c^2$, the rest energy of the electron, and θ, the angle through which the photon E' is scattered relative to the original direction of the photon E_o. It is obvious from the equations that no minimum kinetic energy exists and that $T \to 0$ as $\theta \to 0$. However, a maximum exists at $\theta = 180^o$.

$$T_{max} = E_o \left[1 + (m_o c^2 / 2E_o) \right]^{-1}$$

$$E'_{min} = E_o \left[1 + (2E_o / m_o c^2) \right]^{-1}$$

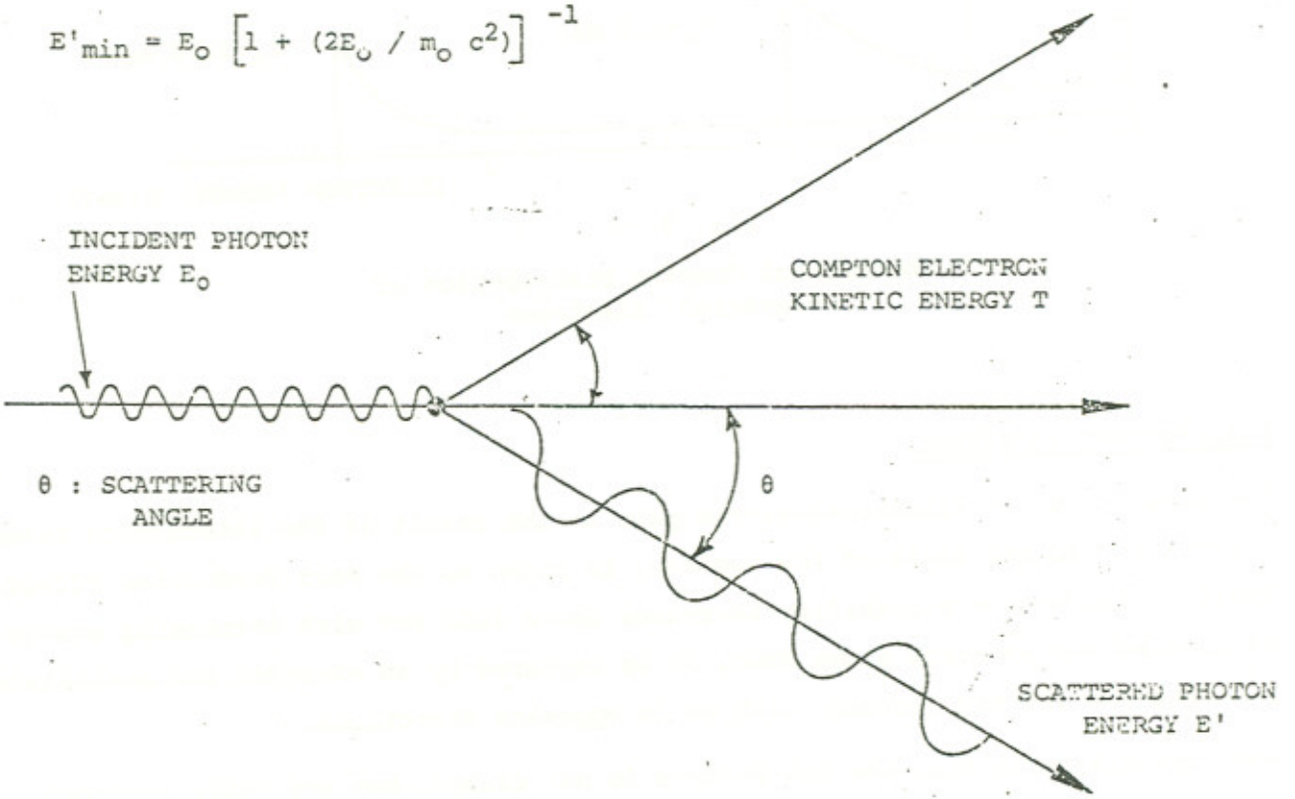

Fig. 6
Compton Interaction

There are 3 possible events which may happen. The first possibility is that the recoil photon escapes, so that an energy of $E_o - E'$ is deposited in the crystal. Since E' can vary from E_o ($\theta=0°$) to $E_o - T_{max}$ ($\theta=180°$) it is clear that the Compton process will give rise to a continuous distribution of pulse heights corresponding to the absorption of the recoil electron from zero to T_{max}.
A second possibility is that the scattered photon does not escape from the crystal, but is absorbed in the crystal following a photoelectric event so that the total energy becomes available. The resulting full-energy pulses add to the photopeak.

It is obvious that intermediate possibilities exist, for example two successive Compton effects, so that some filling-in may take place between the T_{max} Compton edge and the E_o absorption peak.

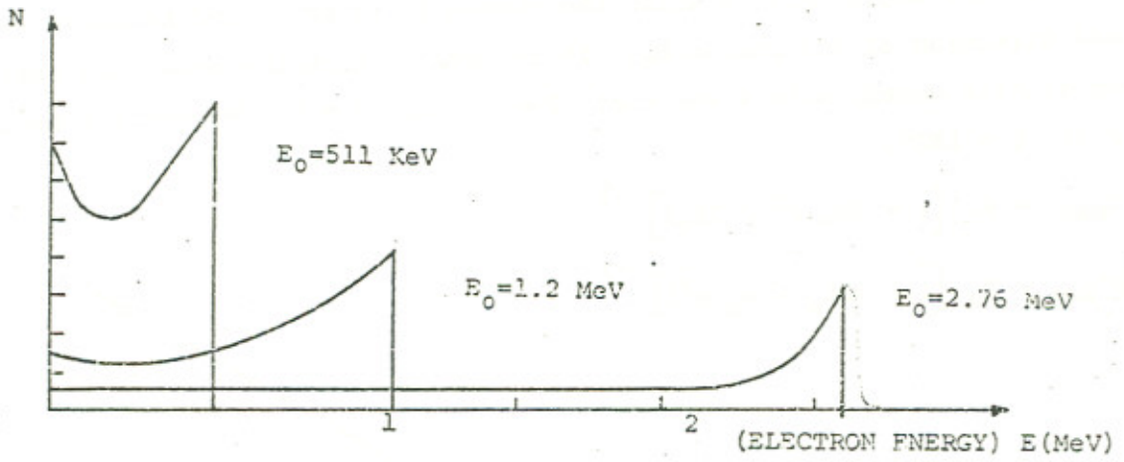

Fig. 7

Theoretical Compton Distribution of Scattered Electrons

Pair Production Effect

The creation of an Electron-Positron pair as the result of the interaction between a gamma-ray in the field of the nucleus, is known as the Pair Production Effect. The Pair Production probability increases above 1022 KeV with increasing energy. As soon as the positron slows down, it is captured by an electron and annihilated yielding two 511 KeV photons which go in opposite directions.

One possibility is that the two photons do not escape, but are fully absorbed through Photoelectric and Compton effects and the resulting "full energy pulse", adds to the photopeak.

A second possibility is that one photon escapes, thus we obtain E_0-511 KeV peak, that is the single escape peak. A third possibility is that the two photons escape, thus we obtain E_0-1022 KeV that is the double escape peak. Intermediate possibilities exist where one or both photons interact through the Compton effect and leave only part of their energy in the crystal, resulting in a continuum between E_0, E_0-511 KeV and the E_0-1022 KeV peaks.