A time to amplitude converter for the measurement of lifetimes in the nanosecond range.

Arnold McAllindon

University of Windsor

Follow this and additional works at: https://scholar.uwindsor.ca/etd

Recommended Citation

McAllindon, Arnold, 'A time to amplitude converter for the measurement of lifetimes in the nanosecond range.' (1965). Electronic Theses and Dissertations. 6395.
https://scholar.uwindsor.ca/etd/6395
A TIME TO AMPLITUDE CONVERTER FOR THE
MEASUREMENT OF LIFETIMES IN THE NANOSECOND RANGE

by

Brother Arnold McAllindon, F.S.C.

A Thesis
Submitted to the Faculty of Graduate Studies through the Department
of Physics in Partial Fulfillment of the Requirements for
the Degree of Master of Science at the
University of Windsor.

Windsor, Ontario
1965
INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.
ABSTRACT

A transistorized time to amplitude converter operating on the overlap principle has been designed. The converter and associated electronics are described and shown to have a mechanical resolving time of $\sim 2 \times 10^{-11}$ seconds.

The calibration procedure is described in detail. First a variable helical delay line is calibrated by a pulse reflection method to within 1%. This calibrated line can then be used to calibrate the converter each time it is used. The method described is simple, fast and accurate.

The overall unit is shown to have a linear region of $\sim 10$ nsec. when fed with 13 nsec. flat topped pulses. These square pulses are formed by a 404A pentode, used as a limiter and a clipping stub.

The analysis of the prompt curve due to a Au$^{198}$ source shows a half width of $\sim .8$ nsec. and a slope in the wings corresponding to a half-life of $2 \times 10^{-10}$ seconds. These values would allow us to measure lifetimes $\geq 1$ nsec. Suggestions of possible improvements are made.
ACKNOWLEDGEMENTS

I would like to thank all those who have helped me to complete this work. My special thanks go to Dr. E.E. Habib, my research supervisor.

I am also indebted to the National Research Council for their financial support in the form of bursaries.
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>11</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>111</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>CHAPTER I - Theoretical Transition Probabilities</td>
<td>1</td>
</tr>
<tr>
<td>A. Radiative Transitions in Nuclei</td>
<td>1</td>
</tr>
<tr>
<td>B. Symmetry Considerations</td>
<td>4</td>
</tr>
<tr>
<td>C. Nuclear Models</td>
<td>6</td>
</tr>
<tr>
<td>D. Experimental Considerations</td>
<td>9</td>
</tr>
<tr>
<td>1. Determination of the Order and Type of Radiation</td>
<td>9</td>
</tr>
<tr>
<td>2. Comparison of Experimental and Theoretical Transition Probabilities</td>
<td>10</td>
</tr>
<tr>
<td>CHAPTER II - Time Analyzers</td>
<td>13</td>
</tr>
<tr>
<td>A. Introduction</td>
<td>13</td>
</tr>
<tr>
<td>1. Lifetimes</td>
<td>13</td>
</tr>
<tr>
<td>2. Types of Clocks</td>
<td>13</td>
</tr>
<tr>
<td>3. Detection</td>
<td>14</td>
</tr>
<tr>
<td>B. Timing</td>
<td>15</td>
</tr>
<tr>
<td>1. Constant Delays</td>
<td>15</td>
</tr>
<tr>
<td>2. Time Fluctuations</td>
<td>15</td>
</tr>
<tr>
<td>(a) Transit Time from Source to Detector</td>
<td>15</td>
</tr>
<tr>
<td>(b) Absorption of Radiation</td>
<td>16</td>
</tr>
<tr>
<td>(c) Decay of the Phosphors</td>
<td>16</td>
</tr>
<tr>
<td>(d) Light Collection</td>
<td>17</td>
</tr>
<tr>
<td>(e) Transit Time through the Photomultiplier</td>
<td>17</td>
</tr>
<tr>
<td>3. Efficiency Fluctuations</td>
<td>18</td>
</tr>
<tr>
<td>C. Resolution</td>
<td>18</td>
</tr>
<tr>
<td>1. Resolving Times</td>
<td>18</td>
</tr>
<tr>
<td>2. Minimum Resolving Times</td>
<td>20</td>
</tr>
<tr>
<td>D. Analysis of the Data</td>
<td>21</td>
</tr>
<tr>
<td>1. Prompt Curve</td>
<td>21</td>
</tr>
<tr>
<td>2. Delayed Curve</td>
<td>23</td>
</tr>
</tbody>
</table>
CHAPTER III - Time to Pulse Height Converter

A. Introduction

B. Classification of Timing Circuits
   1. Delayed Coincidence and Single Channel Analysis
   2. Time Conversion and Multichannel Analysis
   3. Methods of Time Conversion
      (a) Start-Stop Principle
      (b) Vernier Principle
      (c) Pulse Overlap Principle
   4. Choice of Converter Type

C. Circuits and Their Operation
   1. Converter Unit
   2. Limiter
   3. Associated Electronics

D. Experimental Setup

CHAPTER IV - Experimental Behaviour of Apparatus

A. Calibration

B. Resolving Times
   1. In Fast Coincidence Unit
   2. In Converter Unit

C. Analysis of Prompt Curve

D. Conclusions
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Delay Line Conversion Factor</td>
<td>49</td>
</tr>
<tr>
<td>4.2</td>
<td>Prompt Curve Data</td>
<td>58</td>
</tr>
</tbody>
</table>

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
<table>
<thead>
<tr>
<th>Figure Number</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Timing Mechanism</td>
<td>15</td>
</tr>
<tr>
<td>2.2</td>
<td>Sample Decay Scheme</td>
<td>19</td>
</tr>
<tr>
<td>2.3</td>
<td>Coincidence Curves</td>
<td>19</td>
</tr>
<tr>
<td>2.4</td>
<td>Types of Coincidence Curves</td>
<td>24</td>
</tr>
<tr>
<td>3.1a</td>
<td>Time Converter after Start-Stop Principle</td>
<td>29</td>
</tr>
<tr>
<td>3.1b</td>
<td>Time Analyzer after Vernier Principle</td>
<td>29</td>
</tr>
<tr>
<td>3.2</td>
<td>Time Converters after Overlap Principle</td>
<td>32</td>
</tr>
<tr>
<td>3.3</td>
<td>Inputs and Outputs of Overlap Circuits</td>
<td>34</td>
</tr>
<tr>
<td>3.4</td>
<td>Converter Circuit</td>
<td>36</td>
</tr>
<tr>
<td>3.5</td>
<td>Formation of Square Pulses</td>
<td>38</td>
</tr>
<tr>
<td>3.6</td>
<td>Pulse Amplifier</td>
<td>40</td>
</tr>
<tr>
<td>3.7</td>
<td>Experimental Layout</td>
<td>42</td>
</tr>
<tr>
<td>4.1</td>
<td>Calibration of Converter (Apparatus)</td>
<td>46</td>
</tr>
<tr>
<td>4.2</td>
<td>Calibration of Delay Line (Apparatus)</td>
<td>48</td>
</tr>
<tr>
<td>4.3</td>
<td>Calibration of Delay Line (Graph)</td>
<td>49</td>
</tr>
<tr>
<td>4.4</td>
<td>Calibration of Converter (Graph)</td>
<td>50</td>
</tr>
<tr>
<td>4.5</td>
<td>Variable Coincidence Unit</td>
<td>52</td>
</tr>
<tr>
<td>4.6</td>
<td>Linearity of Coincidence Unit</td>
<td>52</td>
</tr>
<tr>
<td>4.7</td>
<td>Au Decay</td>
<td>53</td>
</tr>
<tr>
<td>4.8</td>
<td>Prompt Curve for Au$^{198}$ - Run #8</td>
<td>54</td>
</tr>
<tr>
<td>4.9</td>
<td>Prompt Curve for Au$^{198}$ - Run #13</td>
<td>55</td>
</tr>
<tr>
<td>4.10</td>
<td>Calibration for Au Run</td>
<td>57</td>
</tr>
<tr>
<td>4.11</td>
<td>Response to Variations in P.M. Voltage</td>
<td>60</td>
</tr>
<tr>
<td>4.12</td>
<td>Response to Variations in Energy Selection</td>
<td>60</td>
</tr>
<tr>
<td>4.13</td>
<td>Energy Response of Scintillators</td>
<td>62</td>
</tr>
</tbody>
</table>
CHAPTER I

THEORETICAL TRANSITION PROBABILITIES

A. Radiative Transitions in Nuclei

A complete description of the emission of γ rays from nuclei would require the quantum theory of radiation. The transition probabilities could then be calculated with the aid of the perturbation theory from the formula

$$T_{i\rightarrow f} = \frac{2\gamma}{\hbar} \langle f | H' | i \rangle \left| \begin{array}{c} \frac{dN}{dE} \end{array} \right|^2$$  \hspace{1cm} (1)

where $H'$ is the perturbing interaction and $\langle f | H' | i \rangle$ is the first order matrix element of the interaction taken between the wave function of the initial state $i$ and the final state $f$. The term $\frac{dN}{dE}$ denotes the number of possible final states per unit energy interval. Such a treatment was given by Mosskowski (1955).

However it is possible to gain a physical insight to the problem by a semiclassical treatment whose results can be transformed in a plausible manner to obtain the transition probabilities in terms of the quantum matrix elements given by the more rigorous treatment. In this approach to the problem the nucleus is first regarded as a distribution of charges and currents which vary with time. The classical radiation field emitted by such a distribution can always be expressed in terms of a series of varying multipole moments.
This series expansion will converge rapidly provided the source of radiation is confined to a volume of dimensions small compared to the wavelength of the emitted light. Since $\lambda \sim 2 \times 10^{-11}$ cm. for 1 Mev. $\gamma$ rays, and we are interested only in low energy transitions, the series will converge rapidly in our work.

Starting with a classical system of currents which vary periodically with time,

$$j(x, t) = j(x) e^{-i\omega t} + j^*(x) e^{+i\omega t}$$

and the associated charge distribution, both of which are confined to a small region of space of linear dimension $d$, Blatt and Weisskopf (1952) derived the following expressions for the emission probability of electric and magnetic multipole quanta of energy $\hbar \omega$.

$$T_E(\ell, m) = \frac{8 \pi \ell (\ell + 1)}{\hbar [2\ell + 1]!} \frac{\hbar^{2\ell + 1}}{\hbar} |Q_{\ell m} + Q_{\ell m}^*|^2$$

$$T_M(\ell, m) = \frac{8 \pi \ell (\ell + 1)}{\hbar [2\ell + 1]!} \frac{\hbar^{2\ell + 1}}{\hbar} |M_{\ell m} + M_{\ell m}^*|^2$$

The numbers $\ell$ and $m$ are the quantum numbers associated with the angular momentum $j$ carried by each quantum; in particular

$$|\ell| = \ell(\ell + 1) \quad \text{and} \quad \ell_z = m.$$
parity of electric $2^l$-pole = $(-1)^l$;
parity of magnetic $2^l$-pole = $-(-1)^l$.

The number $K$ is the wave number of the emitted light,

$$K = \frac{\omega}{c} = \frac{1}{\lambda}.$$ 

$Q_{lm}$ and $M_{lm}$ are the electric and magnetic multipole moments arising from the distribution of the periodic charge and current densities respectively.

Because of the intrinsic magnetic moments associated with the spins of the nucleons we must also consider the radiation field emitted by a periodically varying density of magnetization. $Q_{lm}^f$ and $M_{lm}^f$ are the electric and magnetic multipole moments arising from this source.

The transition to quantum mechanics is completed by replacing $j(x)$ and $\rho(x)$ in the classical definitions of the electric and magnetic moments by their quantum mechanical analogues:

$$j(a,b; x) = \frac{e}{2M} \left[ \psi_b^*(x) \psi_a + (x \psi_b )^* \psi_a \right]$$

$$\rho(a,b; x) = e \psi_b^*(x) \psi_a(x).$$

Here we consider a single spinless particle of charge $e$ and mass $M$, moving in some potential field, to go from state $\psi_a$ to a lower state $\psi_b$. $\mathcal{P}$ is the operator for the linear momentum of the particle, $-i \hbar \nabla$. A similar transition must be made for the density of magnetization arising when the particle is considered to have a spin. The generalizations to a system
containing many particles, such as the nucleus, is obtained by a summation on the expressions for a single particle over all the particles in the system.

This approach is naturally going to have limited applicability. The fact that the current sources have to be added one after another is an indication of the empirical nature of the method. Still further additions to the moments would have to be made for phenomena such as the exchange current associated with the exchange forces in nuclei. Before discussing the evaluation of the moments and the transition probabilities, let us see what general conclusions can be drawn from symmetry considerations.

B. Symmetry Considerations

Since the angular momentum of the overall system must be conserved, the angular momentum carried by the \( \gamma \) ray emitted in a transition from state \( \psi_a \) with angular momentum \( I_a \) to state \( \psi_b \) with angular momentum \( I_b \) must be given by the vector difference

\[
l = |I_a - I_b|
\]

and thus can have any non-zero integer value given by

\[
\Delta I = |I_a - I_b| \leq l \leq I_a + I_b.
\]

\( l \neq 0 \) because of the transverse nature of light waves, and hence transitions between states where \( I_a = I_b = 0 \) are strictly forbidden. Moreover, if either \( I_a \) or \( I_b \) = 0 then \( l \) is restricted to the one value \( \Delta I \).
The probability of transition from $\psi_a$ to $\psi_b$ is proportional to the integral

$$\int \psi_b^* 0 \psi_a \, d\tau$$

(10)

where the operator $0$ depends on the nature of the transition. The selection rules for $\gamma$ ray emission are just those combinations of $l$ and parity which give non-vanishing transition probabilities. These rules may be conveniently summarized as follows:

<table>
<thead>
<tr>
<th>Classification</th>
<th>Symbol</th>
<th>Angular Momentum</th>
<th>Parity Change in Nucleus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric $2^l$-pole</td>
<td>$E^l$</td>
<td>$l$</td>
<td>No for $l$ even</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Yes for $l$ odd</td>
</tr>
<tr>
<td>Magnetic $2^l$-pole</td>
<td>$M^l$</td>
<td>$l$</td>
<td>Yes for $l$ even</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No for $l$ odd</td>
</tr>
</tbody>
</table>

In all theories the $\gamma$ transition probability decreases very rapidly with increasing $l$. This can be seen by substituting in equation (3) the classical electric multipole moment given by

$$Q_{l,m} = \int l_m(\theta, \phi) \, \rho(x) \, dv.$$  

(14)

If $d$ denotes the linear dimensions of the source the $Q_{l,m}$ is of the order of magnitude $d^l \epsilon$, where $\epsilon$ is the total charge. From equation (3) we then see that

$$T_E(l,m) \propto (Kd)^{2l}$$

and since $Kd \ll 1$, the emission probability is a rapidly decreasing function of $l$.

The electric multipole radiation originates in the periodic variations of the charge density $\rho$ in the nucleus. The
magnetic radiation has as its source the periodic variations in the current density \( \mathbf{j} \), which is of the order \( \frac{V}{c} \). Hence we would expect that for the same multipole order, the ratio of \( T_M \) to \( T_E \) would be roughly of the order \( \left( \frac{V}{c} \right)^2 \). When the estimation is made using the quantized forms of \( Q_{j,m} \) and \( M_{j,m} \) the result obtained is

\[
\frac{M_{j,m}}{Q_{j,m}} \sim \frac{\mathbf{j}}{MeR} \sim \frac{V}{c}
\]

where the second approximation arises because of the relation \( R \sim \frac{\mathbf{j}}{MV} \) required by the uncertainty principle. This ratio is increased somewhat by the spins of the nucleons which contribute more to the effective magnetic multipole than to the electric multipole.

With these approximations established (strong dependence of \( T_E \) and \( T_M \) on \( \mathbf{j} \) and \( \frac{T_M}{T_E} \sim \left( \frac{V}{c} \right)^2 \)), it is easy to predict the predominant radiations for the transition between states of known angular momentum and parity. The fact that the parity relations would require the competing electric and magnetic radiations to differ in order by one, tends to restrict the radiations to either pure electric or magnetic multipole radiation. The enhancement of the electric multipole by a factor of the order \( \left( \frac{V}{c} \right)^2 \) is experimentally observed in the mixed transitions containing M1 and E2 radiations.

C. Nuclear Models

Equations (3) and (4) give the transition probabilities in terms of the electric or magnetic multipole moments. The
estimation of these moments is strongly dependent on the nuclear model chosen. To illustrate this let us consider two extreme models, the independent single particle model and the liquid drop model. These models are extreme in the sense that in one the motions of the nucleons are highly correlated, while the other is based on the complete independence of nucleon motion.

In the independent particle model a state of the nucleus is described by the quantum numbers of the individual nucleons. The multipole moments between two nuclear states \( \psi_a \) and \( \psi_b \) are different from zero only if the two states differ in the quantum numbers of only one nucleon. Assuming the transition to be a proton going from \( \psi_a, I_a = \ell \) to \( \psi_b, I_b = 0 \), Blatt and Weisskopf have shown that

\[
Q_{\ell m} \sim 4\pi^{-1/2} e^{\frac{3R\ell}{\ell + 3}}, \quad \ell = 1, 2, \ldots
\]  

where \( \ell \) = change in the proton angular momentum.

This is a very crude estimation as they have considered the radial part of the nuclear wave functions to be given by a constant for \( r < R \) and by zero for \( r > R \). Even so, the comparison of experimental and theoretical transition probabilities based on this model shows fair agreement when one takes into account that for \( \gamma \) energies below 1 Mev., the transition probabilities change by a factor of about \( 10^6 \) for unit change in \( \ell \).

The expressions for the transition probabilities predicted by the liquid drop model can be derived by applying
classical electrodynamics to find the rate of radiation from a charged vibrating sphere. The energy of these vibrations has its counterpart in the excitation energy of the nucleus. These radiations can also be classified in the multipole fashion. Lowen (1941) has calculated

\[ Q_{\ell m}(a, b) = 0 \quad \text{(for } \ell = 0, 1) \]

\[ Q_{\ell m}(a, b) = \left( \frac{3}{32\pi} \right)^{1/2} \ell^{1/2} \left( \frac{e}{AM \alpha} \right)^{1/2} Z e R^{\ell - 1} \quad \text{(for } \ell \geq 2). \]

The presence of the total mass of the nucleus AM, and the atomic number Z, in this expression is the result of considering all the charges to move in a common motion. This also has the effect of causing the dipole moment to vanish completely.

If the liquid drop model is a valid approximation then one would expect the electric dipole transitions to be much slower than predicted by the single particle model.

A model which attempts to bridge the gap between the independent particle model and the liquid drop model is the unified model. In the usual shell models the particles are considered to move in an average field generated collectively by all the nucleons. But if collective oscillations were possible then the associated varying field would interact with the particles. The unified model thus describes the nucleus in terms of a coupled system of particles and collective degrees of freedom. In many respects the dynamics is similar to molecules where one has a coupled system of electronic motion and collective rotation and vibrations of the structure as a whole.
With the unified model one hopes to be able to distinguish between particle and collective excitations. The measurement of transition probabilities is an important tool for distinguishing these modes of excitation.

In practice little can be derived from the comparison of individual results because of the uncertainties involved, but valuable information can be obtained from a study of the systematics of the experimental results. Thus far the establishment of the remarkable uniformity in the comparative half-lives of M4 transitions has strengthened the single particle approach in many cases. On the other hand the realization that most first excited states of even-even nuclei have spin 2 and even parity, and that the transition from this state is too fast to be accounted for by a single particle model, has lent much weight to the unified model of Bohr and Mottelson.

D. Experimental Considerations

1. Determination of the order and type of radiation

In order to calculate the transition probabilities one must know the order and type of radiation involved. This implies knowing both the angular momentum and the parity of the initial and final states. Now the spin of the ground state is generally known. Information on the spin and parity of the excited states can frequently be determined by the analysis of $\beta$ disintegration or nuclear reactions which lead to the excited state in question. The study of angular
correlations if accompanied by polarization measurements can yield the type as well as the multipolarity of the radiation. Finally, a very powerful tool for this purpose is the comparison of experimental and theoretical internal conversion coefficients.

It was stated earlier that transitions between states having $I_a = I_b = 0$ were strictly forbidden. Such excited states generally lose their energy by the non-radiative process called internal conversion. In this type of transition the excited nucleus gives up its excitation energy to an atomic electron allowing it to overcome its binding energy, $B$, and escape with the kinetic energy $E$ given by $E = W - B$ where $W$ is the excitation energy of the transition. The number of such electrons ejected from a particular atomic orbit per quantum is called the internal conversion coefficient for that orbit. Since these coefficients depend on electronic rather than nuclear wave functions, they can be calculated theoretically and used to determine the multipolarity of the transition.

2. Comparison of experimental and theoretical transition probabilities

This alternate method of de-excitation has the effect of increasing the transition probability of the state. Therefore before comparing the experimentally determined transition probability with the values given by the theory of electromagnetic radiation one must correct for this phenomenon.

In experimental work the transition probabilities are generally given in terms of the half period of the excited
state. From the theory of radioactivity we know that the half period of a large number of nuclei, each of which has the probability \( \lambda \) of disintegrating per unit time, is given by

\[
T_{1/2} = \frac{\ln 2}{\lambda}
\]

Because of the internal conversion process we must replace \( \lambda \) by \( \lambda_y + \lambda_e \), where \( \lambda_y \) is the probability per unit time of the state decaying by a radiative transition and \( \lambda_e \) the probability per unit time of the state decaying by the non-radiative internal process. Using the total internal conversion coefficient,

\[
\lambda = \frac{N_e}{N_y} = \frac{\lambda_e}{\lambda_y}
\]

which can be determined either experimentally or theoretically, we can now write

\[
T_{1/2} = \frac{\ln 2}{\lambda_y(1 + \infty)}
\]

where \( T_{1/2} \) is the experimentally determined half period. Hence we are now in a position to compare the theoretically predicted transition probability with the experimentally determined quantity.

We have shown that the theoretically predicted \( \gamma \) ray transition probabilities depend on the multipolarity and type of radiation, on the energy of the \( \gamma \) rays, and on the nuclear wave functions of the states involved. All of these quantities can be determined experimentally, except the nuclear wave functions which were shown to depend strongly
on the nuclear model chosen. Hence the experimental determination of the lifetimes of excited nuclei is an important method of investigating the suitability of the various nuclear models throughout the periodic table.
CHAPTER II
TIME ANALYZERS

A. Introduction

1. Lifetimes

The theoretical predictions of the γ ray transition probabilities set $\tau$ in the region of $10^{-6}$ seconds. We will be primarily concerned in measuring lifetimes of about $10^{-9}$ seconds. Most direct measurements of $\tau$ are obtained by measuring the individual lifetimes $T$ of a large number of nuclei and determining the mean value $\tau$ from their exponential distribution. The lifetime $T$ of an individual nuclear state is the interval between its formation and decay which are generally well marked by the emission of some radiation. These events can be used to start and stop a clock which thereby measures the interval $T$.

2. Types of Clocks

If the formation and slowing down process of the particle are well understood the particle itself may be used as the clock. One then measures the distance traversed between the formation and decay, or the velocity at the time of decay. These and other methods such as Coulomb Excitation, resonance particle capture, and scattering experiments lie beyond the range of this thesis. It should be mentioned that these specialized methods are primarily concerned with measurements.
of lifetimes \(<10^{-11}\) seconds and therefore complement the electronic methods discussed here.

The second type of clock is usually an electronic device. Here the emitted radiations are used to start and stop the clock whose scale has previously been calibrated. The clock may be used to control the physical process by which the state is formed, as in pulsed-beam methods, or it may simply detect the random birth and death of the nuclear state as in the coincidence methods used in our experiment.

3. Detection

In the coincidence method the birth and death of the nuclear state under examination are detected by a fast scintillator-photomultiplier combination and the events registered as measurable electrical signals before the timing occurs. This conversion of the transition into a pulse comes only after a succession of interactions which introduce time delays and associated uncertainties. It will be shown that it is these uncertainties which govern the limits and precision of the measurements. Hence our main concern regarding the electronic timing device is that its resolving time \(\langle 2\sigma \rangle\) be at least an order of magnitude better than the statistical broadening \(\langle 2\sigma \rangle\) caused by the detector system. If this is accomplished, the resolving time of the overall timing apparatus will be governed by the detector device alone.
B. Timing

1. Constant delays

It is important to realize from the start that a constant delay in recording the event as an electrical signal will not impede the timing. Only fluctuations in such delays will cause errors in the times measured. These statistical time fluctuations arise from two sources: actual time fluctuations and fluctuations in the efficiency of the recording mechanism.

![Diagram of timing mechanism]

Fig. 2.1. Timing Mechanism.

2. Time fluctuations

(a) Transit time from source to detector

With reasonable geometric care and small detectors this time can be kept negligibly small. When a focussing spectrometer is used, as in our \( \beta \) detector system, a fixed time delay will be introduced. The variation in time due to different paths through the spectrometer has been shown (Bashandy, 1960) to be negligible.
(b) Absorption of radiation

For typical energies, \( \sim 1 \text{ Mev.} \), the slowing down time is of the order of \( 10^{-11} \) seconds. Variations in this time will then be negligible.

(c) Decay of the phosphors

After excitation the scintillator begins to emit light without measurable delay with an intensity which decays very nearly according to an exponential law. For short lifetime measurements, scintillators which decay as rapidly as possible are most suitable. However since the measuring technique depends also on the initial rate of photon emission the photon production efficiency must also be considered. Table I (Devons, 1960) gives decay times and photoelectric efficiencies of some commonly used scintillators.

**TABLE I**

Scintillator Data

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Decay Time ( \tau ) (10^{-9} \text{ sec.})</th>
<th>Photoelectric efficiency referred to NaI(Tl) ( \eta / \tau )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthracene</td>
<td>30</td>
<td>0.80</td>
</tr>
<tr>
<td>Plastic Phosphor (NE102)</td>
<td>3</td>
<td>0.45</td>
</tr>
<tr>
<td>Liquid (toluene-terphenyl-POPOP)</td>
<td>3</td>
<td>0.38</td>
</tr>
<tr>
<td>Stilbene</td>
<td>8</td>
<td>0.38</td>
</tr>
<tr>
<td>NaI(Tl)</td>
<td>250</td>
<td>1.0</td>
</tr>
</tbody>
</table>

* Used in our experiment.
(d) *Light collection*

This time delay and its fluctuations are kept at a minimum by using a compact setup and good optical contacts. Since the \( \beta \) detection is accomplished in a high field intensity region, a light pipe must be used to guide the light from the scintillator to the photomultiplier tube outside the field. Post (1952) estimates the variation in time due to a light pipe one foot long to be \( 10^{-10} \) seconds. Since our light pipe is only about two inches long we can hope that its effect on the timing will be negligible.

The preceding four factors combine to give a random fluctuation in the time of emission of photoelectrons from the photocathode. Under good experimental conditions the rate of decay of the excited states (c) becomes the governing factor in this fluctuation.

(e) *Transit time through the photomultiplier*

Due to its special electron optical properties, the transit times through the 56 AVP tube are constant to less than \( 3 \times 10^{-10} \) seconds at a voltage supply of 2000 volts. This variation can be reduced further by careful adjustment of the focusing electrode or by working at still higher voltages. The tube can handle 3000 volts. Since this variation is of the same order of magnitude as that due to the crystal, it will have to be incorporated into the analysis of the results.
3. **Efficiency Fluctuations**

Because of the manner in which the electrical pulses will be used to determine the lifetimes, the shape and size of photomultiplier pulses should be constant. Provided care is taken to ensure a good optical system, the variations in the pulse due to variations in the efficiency of collecting the light emitted by the scintillator will be negligibly small. However the light output of the scintillator will vary with the amount of energy absorbed from the incoming particle. To overcome the resultant time jitter, use is made of the fast-slow principle first proposed by Bell and Petch (1949). In this setup the energy selection is carried out in a slow branch while the timing is performed with the fast pulses. These three pulses (2 slow, 1 fast) are then fed into a triple coincidence circuit which gates the analyser thereby ensuring that timing information due only to relevant radiations is analyzed.

Because of the numerous sources of time fluctuations, the actual time intervals involved and their probable time distributions are not calculated. Rather they are minimized experimentally and their residual effects are considered in the analysis of the experimental results.

C. **Resolution**

1. **Resolving Times**

Let us suppose that we are viewing the system shown in Fig. 2.2 with a coincidence circuit of infinitely small
resolving time \((2\sigma)\). If for the moment the lifetime \(\tau\) is set equal to zero (i.e. transitions A and B are simultaneous) we could count the number of coincidence pulses derived from transitions A and B occurring per unit time interval. If we now delayed pulse A with respect to pulse B the coincidence count would drop to zero. Hence the coincidence curve, coincidence counts vs. time delay, would have a delta function characteristic (Fig. 2.3a). If the excited nuclear state were now given a mean life \(\tau\), the coincidence curve for delayed A pulses would take on an exponential shape (Fig. 2.3a).

However things are not that ideal. The fluctuations in the timing mechanism described above cause the delta function
to exhibit a half width $2\sigma$. Furthermore since the resolving time of the coincidence circuit $(2\phi)$ is generally not negligible with respect to $2\sigma$, the actual coincidence curve due to a prompt source will have a half width $2\tau_c > 2\sigma$.

2. Minimum Resolving Times

If we consider the time fluctuations due to variations in pulse height to be overcome by our fast-slow coincidence circuit, we are left with two main sources of time fluctuations: the decay of the optical states in the phosphor and the transit time fluctuations through the photomultiplier tube.

Post and Schiff (1950) published their work on the spread of the prompt spectrum due only to the phosphor decay time which they characterized by a single decay constant $\lambda_p$. If the average total number of photoelectrons produced by a single transition particle is $R$, they calculated that the mean time delay for the appearance of the $q^{th}$ photoelectron is

$$\bar{\tau}_q = \frac{q}{R\lambda_p} \left[ 1 + \frac{q+1}{2R} + \ldots \right]$$

and the fluctuation in $\bar{\tau}_q$ is

$$\Delta \bar{\tau}_q = \frac{q^{1/2}}{R\lambda_p} \left[ 1 + \frac{2(q+1)}{R} + \ldots \right]^{1/2}$$

where $R \gg 1$ and $q \ll R$.

From this expression we see that provided the anode pulse due to the first photoelectron is large enough to operate the timing circuit, the minimum resolving time should
be achieved by timing with the pulse due to the first photo-electron. However the presence of the transit time jitter of equal magnitude through the photomultiplier tube tends to make this analysis inadequate.

In 1959 Gatti and Svelto performed a detailed analysis on the prompt response in which both the scintillator time decay and the photomultiplier time jitter were taken into account. Sugarman, Li and Schwarzschild (1962) have shown experimental evidence which agrees qualitatively with the theoretical predictions. Their curves indicate that the minimum resolving time is obtained when one works with a reasonably large portion (~0.2) of the plate signal rather than with the minimum portion predicted by Post and Schiff.

In most practical cases the three factors of scintillator decay, transit time spread and pulse height variation, all contribute to the experimental resolving time. The minimum resolving time and the manner of obtaining it will depend on how well these effects are minimized in a particular experimental setup.

D. Analysis of the Data

1. Prompt Curve

On the basis of Post and Schiff's analysis one would expect the minimum resolving time to be governed by the statistical fluctuations in the arrival time of the qth photoelectron as given by equation (2). Typical values of
q = 25, R = 75, \gamma_p = 2.5 \times 10^{-9} \text{ sec. for a fast liquid phosphor, give } \Delta \gamma = 2.5 \times 10^{-10} \text{ sec. The problem now is to show how two counters each being fed by pulses having this statistical time fluctuation will react. El-Wahab and Kane (1962) have derived expressions for the time response functions of scintillation counters using a mathematical model to introduce various time spreads. The first case they consider is the one given above where the time spread is considered to be due only to the finite decay time of the scintillators. If the differential probability of observing the \( n \)th photoelectron of the total number \( N \) given off by one event is given by \( R_n(t) \), then the response of two scintillation counters in coincidence will be given by the overlap integral

\[
R_{n1}^{N1} R_{n2}^{N2} (T) = \int_{0}^{\infty} R_{n1}^{N1} (t_1) R_{n2}^{N2} (t_2) \delta(t_1 - t_2 + T) \, dt_1
\]

where \( T \) is the relative time delay between the counters.

They then go on to show that for large time delays the solution of this integral can be written in the form

\[
R_{n1}^{N1} R_{n2}^{N2} (T) = \sum_{m = n_2 - n_1 + 1}^{N_2} A_{n1n2m} e^{-m \Delta \gamma T}
\]

where the \( A \) terms depend on parameters other than \( T \). We note that in the limit when the timing is accomplished using the first photoelectron this expression gives the same slope in the wings as that given by Post and Schiff.

In attempting to obtain this experimentally Bell, Graham and Petch (1952) found that they had to assume a statistical
delay due to transition time effects in the photomultiplier
tubes of approximately $2 \times 10^{-10}$ seconds. In their second
calculation El-Wahab and Kane introduced a second exponential
delay to approximate the photomultiplier transit time vari-
tations. Although the results could not be expressed in a
closed exponential form they were able to calculate the
effects of various ratios of $\lambda_2/\lambda_1$ on the half width of the
prompt curves. A comparison of the graphical results for
the single and double time variations emphasizes the advant-
ages of keeping $N/n$ as large as possible.

2. **delayed Curve**

The method used to derive the lifetime of a nuclear
state from a measured time distribution depends on the rela-
tive magnitude of the lifetime to the properties of the
prompt spectrum, its half width and its slope in the wings
expressed as an apparent half life. It was previously men-
tion that the objective was to keep the experimental half
width of the prompt curve $2\tau_0$ as small as possible. This is
because it allows for easier and more accurate analysis. In
Fig. 2.4 the prompt resolution curve is represented by $P(x)$
and the delayed curve by $F(x)$, where $x$ is the artificial
delay. If there is a measurable lifetime the daughter emis-
sion has a probability $f(t)\, dt$ of occurring $t$ seconds after
the parent emission. If $P(x)$, $F(x)$ and $f(t)$ are all normal-
ized to unit area then

$$F(x) = \int_{-\infty}^{\infty} f(t) \, P(x-t) \, dt . \quad (5)$$
Newton (1950) has shown that if only a single decay is involved, whose mean life is \(1/\lambda\), then \(f(t) = 0\) for \(t < 0\), and \(f(t) = \lambda e^{-\lambda t}\) for \(t \geq 0\). Using these expressions for \(f(t)\) and substituting \(y = x - t\), equation (5) becomes

\[
F(x) = \lambda e^{-\lambda x} \int_{0}^{x} e^{\lambda y} P(y) \, dy.
\]  

(6)

Differentiating (6) gives

\[
\frac{dF(x)}{dx} = \lambda \left\{ P(x) - F(x) \right\}.
\]  

(7)

and

\[
\frac{d}{dx} \left[ \ln F(x) \right] = -\lambda \left\{ 1 - P(x) \left[F(x)\right]^{-1} \right\}.
\]  

(8)

From equation (7) we see that the maximum of \(F(x)\) occurs at its intersection with \(P(x), x_0\); while equation (8) shows...
when $\lambda$ can be determined by the slope of the tail of $f(x)$.

If $\tau < 2\tau_0$ then the slope method obviously cannot be used. Bay (1950) has shown that in this case the centre of gravity of the delay curve will be displaced from that of the prompt curve by the mean life of the daughter nuclei. In practice this method is extremely difficult to carry out as it requires a very fine matching of the prompt and delay spectra. Hence every effort is made to keep $2\tau_0 < \tau$, in which case the slope method may be used in the region where $P(x) \ll F(x)$ has been satisfied.
CHAPTER III

TIME TO PULSE HEIGHT CONVERTER

A. Introduction

In the previous chapters we have seen how the nuclear events associated with the birth and death of a nuclear state can be transformed by means of a scintillator-photomultiplier combination into an electrical pulse. The uncertainties in the time of arrival of these pulses were then related to the resolution and shape of the coincidence curves. The measurement of the lifetime of the state has then been reduced to the electronic problem of measuring the time interval between the arrival of two pulses. Many electronic devices have been developed for this purpose. They may be conveniently divided into two main groups depending on whether they use the delayed coincidence method with single channel analysis or the method of time conversion with multichannel analysis.

B. Classification of Timing Circuits

1. Delayed Coincidence and Single Channel Analysis

In its simplest form the single channel analyzer consists of a coincidence circuit combined with a circuit to provide variable time delay in the arrival of the pulses at the coincidence unit. The coincidence unit tells whether or not the
two pulses arrived within a given time interval \((2\tau_0)\), called the resolving time of the coincidence circuit. Under ideal conditions one could then determine the decay constant \(\lambda = 1/\tau\) from the exponential slope of the coincidence curve obtained by the stepwise delay of the first pulse. Such a unit was used in Chapter II(C) to define the resolution of the prompt curve \(2\tau_0\), which includes the effects of both the finite electronic resolving time \(2\rho\), and the statistical broadening \(2\sigma\) due to the detection process. The discussion of the analysis of the results has indicated the advantages of keeping \(2\tau_0\) as small as possible. However even if \(2\rho \ll 2\sigma\) could be obtained the overall efficiency of the experiment would be severely decreased. The resulting high time consumption could prove troublesome with respect to apparatus stability and source alterations. An early attempt to reduce this time element consisted of using a series of single channel analyzers linked together to form chronotrons. However the appearance of multichannel pulse height analyzers and the development of the principle of time conversion soon replaced this cumbersome and restrictive technique.

2. Time Conversion and Multichannel Analysis

Time conversion consists in the linear transformation of the time interval between two pulses into a third observable factor. In our case the time interval is converted into a pulse height. These pulse heights are then fed to a multichannel pulse height analyzer. Thus instead of the coincidence
curve being a time spectrum, it now becomes a pulse height spectrum (i.e., coincidence count rate vs. pulse height). With this system the stepwise delay necessary in the coincidence method is eliminated and the complete spectrum is taken at once. Each channel represents a coincidence circuit of resolving time $2\phi$ given by the channel width. Furthermore $2\phi$ can now be made much smaller than $2\sigma$ without affecting the efficiency. We can therefore obtain

$$2\phi \ll 2\sigma$$

and

$$2T_0 \sim 2\sigma.$$  

There are numerous ways of applying the time conversion principle but most are based on one of the following fundamental methods: the start-stop, the vernier, and the pulse overlap methods.

3. **Methods of Time Conversion**

(a) **Start-stop principle**

In this method the start pulse $A$ causes the linear charge or discharge of a capacitor to begin, and the process is ended by the arrival of pulse $B$. The charge on the capacitor is then linearly proportional to the time interval between pulses $A$ and $B$. An example of such a circuit is shown in Fig. 3.1a, taken from Beghian (1958). This circuit is also of interest to us because of the use of cable clipping in forming the start-stop pulses. Before the arrival of the pulses, tubes $V_1$ and $V_2$ are conducting, while $V_3$ and $V_4$ are cut off. The arrival of $A$ causes the grid of $V_4$ to
Fig. 3.1a. Time Converter after Start-Stop Principle.

Fig. 3.1b. Time Analyzer after Vernier Principle.
rise, with the result that the capacitor C begins to discharge linearly. The arrival of B causes V_3 to conduct thereby cutting off V_4. This circuit has the disadvantage, characteristic of most start-stop circuits, of producing an output signal for a single input pulse. This necessitates the addition of a supervisory circuit which will accept only pulses corresponding to two input pulses. Although the electronic resolving time obtained with the aid of a pulse generator is generally no better than 2 \times 10^{-10} seconds, these circuits do provide a rather large linear range, spreading in some cases as high as 200 nanoseconds.

(b) Vernier principle

In this method the time interval to be measured is first expanded by a known factor. This is accomplished by allowing two oscillations with periods T_1 and T_2 which differ only slightly from each other to be started by events A and B. If the time interval to be measured, \( \tau \), is situated between the beginning of the two oscillations, the oscillations will be in phase only after a time expressed by \( \tau' = \tau \frac{T_2}{\Delta T} \) where \( \Delta T = T_1 - T_2 \) and \( T_1 \approx T_2 \). The problem then reduces to determining the first in-phase state of the two oscillations with the aid of a phase sensitive element. This principle has been applied directly to the start-stop method but does not increase the resolution of that method significantly.

However the time expansion can be used directly in another unit illustrated in Fig. 3.1b, taken from Lefevre (1957). This analyzer consists of two transmission lines of
slightly different periods which are fed by two time marking
generators reacting to the events A and B. The delayed pulse
B travels the shorter route and coincides with A after \( n = \frac{T}{\Delta T} \) cycles. At just this moment the fast coincidence circuit
responds to return both generators to their initial position.
The series of \( n \) pulses is fed directly to the input of a
multichannel memory and hence overcomes the difficulties of
calibrating the kicksorter scale. The authors do not give a
mechanical time resolution but a prompt coincidence curve of
\( \text{Co}^{60} \), using fast plastic scintillators yielded a half width
of 0.85 nanoseconds.

\textbf{(c) Pulse overlap principle}

The pulse overlap method relies on the ability of the
converter unit to give out a pulse which is proportional to
the overlap time of the two input pulses. The timing process
can be performed with either valves or semiconductors. Fig.
3.2a from Green and Bell (1958) shows the use of the gated
beam tube 6BN6 at reduced working voltages in order to enable
it to be operated with inputs of about 1 volt. This tube
will conduct a constant current only if both grids are driven
positive from cutoff at the same time. The voltage in the
output capacitor will decrease linearly during this time of
overlap. Similarly in the transistorized converter due to
Simms (1961), Fig. 3.2b, the capacitor will receive current
from \( T_3 \) only during the time that both \( T_1 \) and \( T_2 \) are biased
off by the input pulses A and B. The response of these cir-
cuits can be characterized by the input pulses and output
response shown in Figs. 3.3a and b. If the time delay between pulses A and B is T, then as T increases the output of the converter will decrease. Since the delay T could be inserted so as to delay either A or B the output of the converter will be symmetric about T=0. This symmetric response will cause the chance coincidence counts to be doubled.

The idea of simultaneous recording of all the pulse heights with a multichannel analyzer is now obvious. First a fixed delay T is inserted before pulse B so that the pulse height due to a prompt event (i.e., A and B occur simultaneously) falls at some point P in the linear response region. If B were now given a mean life $\bar{T}$ and the output of the converter fed to a multichannel pulse height analyzer, the coincidence curve (coincidence count rate vs. channel number) will be exponential in form, and $\bar{T}$ could be determined from its slope.

From Fig. 3.3b it can also be seen that with the aid of a discriminator the converter could be used as a fast coincidence unit with a resolving time $2\sigma < 2\bar{\tau}$. In fact a variable discriminator would give a unit with variable resolving time.

4. **Choice of Converter Type**

Most of the electronic circuits available have a resolving time $2\sigma$ sufficiently small to keep $2\bar{\tau} \approx 2\sigma$. Hence in choosing a given circuit other factors such as the ease of construction, and calibration, the stability with respect to
Fig. 3.3. Inputs and Outputs of Overlap Circuits.
temperature and time, and the particular applications foreseen should all be taken into account. Because our laboratory was already equipped with a magnetic lens spectrometer, scintillator-photomultiplier probes, a variable coaxial delay line, and a multichannel pulse height analyzer, some time conversion method was definitely favoured. Taking advantage of our experience with some fast semiconductors previously used in the laboratory, a semiconductor time converter after the overlap pulse method was designed.

C. Circuits and Their Operation

1. Converter Unit

The converter circuit shown in Fig. 3.4 consists of a constant current source (2N274) feeding the input diodes (HD5000) and the fast switching output transistor (2N502). In the quiescent state the 2N502 is biased off so that the constant current $I$ flows through the branched diodes. If a positive pulse, sufficiently large to cut off diode A arrives at input (1), the complete current $I$ will flow through diode B, the 2N502 being sufficiently biased to withstand the small increase in voltage at P. However, if input pulses of sufficient size arrived simultaneously then both diodes would be cut off and the current $I$ would flow through the 2N502 and be integrated in the collector circuit. The voltage at C would then be given by

$$ V = \frac{1}{C} \int_{-\infty}^{\infty} I \, dt $$
Fig. 3.4. Converter Circuit.
and since $\alpha I$ is constant,

$$v = \frac{\alpha I}{c} t \Delta$$

and we see that the output voltage will be directly proportional to the overlap time of the input pulses.

The constancy of $I$ can be seen through the inspection of the dynamic collector impedance of the 2N274 used. It was observed that

$$\left| \frac{\Delta V_c}{\Delta I_c} \right| I_c = 4 \text{ ma} = 50 \text{ K}.$$  

Now the largest change in $V_c$ is of the order of 1 volt, which would lead to 0.5% change in $I_c$. But since we are primarily concerned with the constancy of $I_c$ during overlap time, the change in $V_c$ will be only of the order of .3 volts and hence $I_c$ will change by much less than 0.5%.

Since the room temperature can be held constant to within a few degrees, variations in $\alpha$ with respect to temperature will be negligible.

2. Limiter

In discussing the converter it was assumed that the pulses were rectangular. For proper operation of the converter these pulses should be uniform, fast rising, flat topped pulses. To obtain these pulses a current stabilized 404A sharp cut off pentode is used as a limiter (Fig. 3.5). The fast rising large negative pulses from the photomultiplier anode are fed to the grid of the pentode, cutting it off and causing the anode to limit sharply.
Fig. 3.5. Formation of Square Pulses.
The plate load consists of a 2.2 K resistor in parallel with the 100 ohm stubbing cable and converter cable. With this arrangement we have been able to obtain pulses with rise times of ~3 nsec. and flat tops of ~13 nsec.

3. Associated Electronics

To make the instrument more versatile the converter is followed by two units each containing an attenuator, an amplifier and a discriminator. The constant gain high frequency amplifier used was designed in this laboratory by H. Young. The complete amplifier circuit is given in Fig. 3.6. The estimated values of the input and output resistance are $Z_i \sim 11.5 \, \text{K}$ and $Z_o \sim 3 \, \text{K}$. The unloaded gain was found to be given by $A_v \sim \frac{R_3 + R}{R} \sim 10$. The estimations involved in calculating these values were setting $r_b \sim 1 \, \text{K}$ and $r_e \sim 20 \, \Omega$ for each transistor, and assuming that $I_c \sim I_g$.

The attenuators are straight resistive units each having the attenuation factors 1/2, 1/4 and 1/8. They are used only if the maximum output of the converter causes either amplifier to limit. The overall gain of the unit can be varied from ~1.5 to 100.

The discriminators are conventional diode units. The first discriminator serves two purposes. It can be used to reject all or part of the output of the converter which is due to prompt events. In this way a closer analysis of the wing of the delayed curve could be made. The other application is to use this discriminator to form a fast coincidence unit of variable resolving time as discussed above. There
is a disadvantage of having this diode discriminator in the circuit because it introduces a nonlinearity of about .3 volts (time during which diode is shutting) which is then amplified with the rest of the pulse. It was to overcome this nonlinearity that the second discriminator was added after the amplifiers. It can be varied with the second attenuator so as to limit the nonlinearity in the final pulse to .3 V.

D. Experimental Setup

The complete experimental setup is shown in Fig. 3.7. A thin source of the radioactive element decaying to the excited nuclear level under study is placed between the magnetic lens spectrometer and the scintillator-photomultiplier combination.

The magnetic lens spectrometer is of the Gerholm type and has been extensively treated in theses by J. Colclough (1963) and H. Young (1964). This type of lens is well suited for lifetime measurements since one can study $\beta - e$ or $\beta - \gamma$ processes with it depending on whether the movable lens or the angular correlation table is mounted. When used in $\beta - \gamma$ experiments the instrument is capable of a transmission of 1.8% and a resolution of 3% for a 5 mm. source (Young, 1964). The power for the lens is delivered by a 0-60 ampere current supply with negligible drift and which changes less than .01% for a 10% change in line voltage or a $10^\circ$ change in room temperature (Colclough, 1963).
Fig. 3.7. Experimental Layout.
P.M. - Photomultiplier Tube
P.H.A. - Pulse Height Analyser
The scintillators used to detect both the $\beta$ and $\gamma$ particles were plastic scintillators (NE102) coated with MgO.

Two Philips 56AVP photomultiplier tubes were used because of their slight transit time fluctuations ($< 3 \times 10^{-10}$ sec.), and their ability to deliver large peak currents and high gains. For the fast timing the pulses are taken from the anode (14th dynode), while the slow pulses used in the energy selection process are taken from the 10th dynode.

The fast pulses are then shaped by the limiter and clipping stub before being fed to the converter. The converter pulse which is proportional in height to the actual life of one excited nucleus, then goes through the amplifier stage and a coaxial delay line to the input of the multichannel analyzer. The delay line is set so that the analyzer is gated according to the specifications required by Technical Measurements Corporation Model 404-A. The printer and delay line were also T.M.C. units.

The gating of the multichannel analyzer is set up to ensure that only timing information due to events which have lost a specified amount of energy in the scintillators will be analyzed. The energy selection is performed by two Philips pulse height analyzers. The triple coincidence circuit, which is fed by the two slow pulses, and a multivibrator pulse caused by a fast coincidence pulse, ensures that the timing as well as the energy loss in the scintillator is right for analysis.
The multivibrator consists of two monostable multivibrators used to delay the fast pulse sufficiently so as to overcome the time jitter in the Philips pulse height analyzers. The counting assembly, precision timers, printer control, pulse height analyzers and power supplies are all from the Philips Project 111.540. The scalers and printers have been omitted from Fig. 3.7.
CHAPTER IV

EXPERIMENTAL BEHAVIOUR OF APPARATUS

A. Calibration

From the discussion of the time conversion principle it is apparent that the time to pulse height conversion factor will depend on the properties of the converter, amplifier, and associated circuits. Since these may not remain constant over long periods of time, some quick accurate method of calibrating the apparatus is desirable.

In 1962 Graham et al. described their air-cored helical delay line method of calibration. The apparatus with our modifications is shown in Fig. 4.1. From this diagram it is seen that a change in the junction position of $\Delta x$ leads to a change in the relative times of arrival of the pulses at the converter of $\Delta t = \frac{2\Delta x}{v}$, where $v$ is the propagation velocity in the delay line. They estimated that the lucite pegs used to support the central conductor would reduce the velocity of the signal by 1%. The estimation was then checked by comparing the results of this method with the positron-annihilation method. The two calibration scales differed by $0.7 \pm 0.7\%$. The physical dimensions of the delay line were such that one complete rotation introduced a relative time change $\Delta t = 2.4 \text{ nsec}$. The mechanical reproducibility of the input junction is $< 1 \text{ mm}$, which corresponds to a reproducibility in time of $\sim 10^{-12} \text{ nsec}$. 

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Fig. 4.1. Calibration of Converter.
Since our delay line was built to the same specifications, the conversion factor (nsec. per rotation) is expected to be close to their value. The apparatus shown in Fig. 4.2 was set up to check this result experimentally. With a stub of transit time L/2 determining the time length L of the generator pulse, the diode discriminator is moved along the delay line to determine the point A, the farthest distance from the open end at which overlap of the input and reflected pulses can fire the discriminator. The standard cable of time length L/2 is then added to the stub and the experiment repeated to determine the corresponding point B. The difference, A - B, is then equivalent to the time length L/2 of the standard cable. The results of a typical run are shown in Fig. 4.3. Table 4.1 contains the results obtained while varying the bias voltage.

For our standard cable we used a General Radio patch cord equivalent to 86±0.2 cm. of air. Taking the possible error in the readings of A and B to be ±0.003, the possible percentage error in the conversion factor is 0.5%.

Having assured ourselves that one rotation of the delay line introduces a relative time delay of 2.4 nsec. to within 1%, we may now use the delay line to calibrate the converter unit each time it is used. This method is particularly attractive in that the converter can be calibrated without interrupting the experimental setup. The delay line is simply connected as shown in Fig. 4.1 and the output is analysed as the delay line position is varied. A typical calibration

*Private communication from General Radio Company.
Fig. 4.2. Calibration of Delay Line.
Fig. 4.3. Calibration of Delay Line.

TABLE 4.1
Delay Line Conversion Factor

<table>
<thead>
<tr>
<th>Voltage</th>
<th>A - B (Rotations)</th>
<th>Time Rotation</th>
<th>% Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>2.417</td>
<td>1.186</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>2.390</td>
<td>1.199</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>2.403</td>
<td>1.193</td>
<td>0.1</td>
</tr>
<tr>
<td>1.3</td>
<td>2.402</td>
<td>1.193</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>2.423</td>
<td>1.183</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>2.396</td>
<td>1.196</td>
<td>0.3</td>
</tr>
<tr>
<td>1.4</td>
<td>2.405</td>
<td>1.192</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>2.383</td>
<td>1.203</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>2.420</td>
<td>1.184</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Conditions: input pulse, 1 V., 40 nsec.; $\tau/2 = 2.867$ nsec.
Fig. 4.4. Calibration of Converter.

Conversion Factor
0.15 nsec./channel
curve is shown in Fig. 4.4. The 20 nsec. clipping cable
gave input pulses having a rise time of ~3 nsec. and a flat
top of 13 nsec. This gave a linear region of ~8 nsec. This
region could be lengthened by increasing the length of the
clipping cable. Nonlinearity sets in at the high converter
outputs because of the finite rise time of the pulses, while
the low output nonlinearity is due to the diode discriminator.
When the converter is to be used to measure a lifetime, care
must be taken that the maximum output falls in the linear
region. This is easily done by inserting a constant delay
before one of the inputs to the converter.

B. Resolving Times

1. In Fast Coincidence Unit

When used as a fast coincidence unit the detailed analy-
sis of the converter pulses is not necessary because we are
only interested in knowing whether or not the events occurred
within a set time \(2\rho\) — the coincidence resolving time. The
time \(2\rho\) is governed by the time length of the clipping pulses
\(L/2\). When used in this manner the converter will give an
output, which is used to pulse a counter, every time the
events feeding the converter occur within the time \(2L\). If
the converter output is now discriminated against, the resolv-
ing time \(2\rho\) will be less than \(2L\), Fig. 3.2. Figure 4.5 shows
the coincidence counting rate as a function of the relative
time delay between the pulses (given in terms of delay line
position) for various discriminator settings. The resolutions
Fig. 4.5. Variable Coincidence Unit.

Delay Line Reading

F 7.50-----7.60
C 10.80-----10.90
A 12.65-----12.75

Run
B 134
C 113
D 71
E 45
F 0

Fig. 4.6. Linearity of Coincidence Unit.
(defined as full width at half the maximum count rate) obtained for various discriminator settings are tabulated in Fig. 4.5 and plotted in Fig. 4.6 to show the linear relation between the resolution and the discriminator setting.

2. In Converter Unit

When used for time conversion the resolving time ($2\sigma$) is given in terms of the channel width and is evaluated from the calibration curve. The limiting factor now becomes the electrical stability of the converter and associated units. This electronic resolving time can be determined by using the apparatus as shown in Fig. 4.1. The electronic resolving time will be the half width of the curve obtained for fixed pulses and a constant delay line setting. This half width was found to be less than $2 \times 10^{-11}$ sec., well within the statistical broadening caused by the present detector system.

C. Analysis of Prompt Curve

A $^{198}$Au source was used to obtain the prompt curve. Its simple decay scheme, Fig. 4.7, and the $2 \times 10^{-11}$ seconds half-life of the $^{198}$Hg excited state, make it ideal for our purposes. Figures 4.8 and 4.9 show the prompt curves obtained in two typical runs. In each run the pulses were delayed with respect...
Fig. 4.8. Prompt Curve for Au$^{198}$ - Run #8.

$T_{1/2} = 1.8 \times 10^{-10}$ sec.
Fig. 4.9. Prompt Curve for Au$^{198}$ - Run # 13.

$T_{1/2} = 1.6 \times 10^{-10}$ sec.
to the \( ^7 \) pulses so that the peak of the prompt curve fell in
the linear region of the calibration curve, Fig. 4.10. The
characteristics of the curves, their full width at half
maximum \( \omega_{1/2} \) and the slope in the wings expressed as a half-
life \( T_{1/2} \), are presented in Table 4.2.

As was predicted the wings of the curve do fall off
exponentially. The slope in the wings corresponds to a half-
life of \( 2 \times 10^{-10} \) seconds. The half widths are less than 1
nsec. and hence we would be able to measure lifetimes of
this order by the slope method.

The curves depart from the exponential slope in both
the low and high channel regions, the departure being more
pronounced in the low region. These departures although low
in number would cause difficulties in the measurement of
lifetimes close to the value of \( \omega_{1/2} \).

The calibration curve, Fig. 4.10, indicates complete
linearity between channels 10 and 80. Since the departures
from the exponential shape occurs before reaching the non-
linear region of the converter, the problem does not seem
to lie in the converter unit.

Departures of this nature have been observed by previous
experimenters and have generally been attributed to pile-up
effects due to high single channel count rates (\( 10^4 \) per sec.)
Schwarzschild (1962). Although our single count rates were
one order of magnitude lower than the quoted rate, the fact
that similar measurements made after the source had decayed
by six half-lives showed no tendency to depart from the
Slope = 22.3 \text{ channels/rotation}

Conversion Factor = 1.1 \times 10^{-10} \text{ seconds/channel}

Fig. 4.10. Calibration for Au Run.


<table>
<thead>
<tr>
<th>Run No.</th>
<th>High Voltage</th>
<th>Energy Selection</th>
<th>Centroid</th>
<th>$\omega_{1/2}$</th>
<th>$T_{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beta</td>
<td>Gamma</td>
<td>Beta</td>
<td>Gamma</td>
<td>(Channel No.)</td>
</tr>
<tr>
<td>1*</td>
<td>2200</td>
<td>2200</td>
<td>400</td>
<td>100</td>
<td>250</td>
</tr>
<tr>
<td>2</td>
<td>2200</td>
<td>2200</td>
<td>307</td>
<td>87</td>
<td>250</td>
</tr>
<tr>
<td>3</td>
<td>2200</td>
<td>2200</td>
<td>482</td>
<td>137</td>
<td>250</td>
</tr>
<tr>
<td>4</td>
<td>2200</td>
<td>2200</td>
<td>400</td>
<td>100</td>
<td>250</td>
</tr>
<tr>
<td>5</td>
<td>2200</td>
<td>2200</td>
<td>219</td>
<td>62</td>
<td>250</td>
</tr>
<tr>
<td>6</td>
<td>2200</td>
<td>2200</td>
<td>200</td>
<td>450</td>
<td>250</td>
</tr>
<tr>
<td>7</td>
<td>2200</td>
<td>2200</td>
<td>200</td>
<td>450</td>
<td>175</td>
</tr>
<tr>
<td>8</td>
<td>2200</td>
<td>2200</td>
<td>200</td>
<td>450</td>
<td>140</td>
</tr>
<tr>
<td>9</td>
<td>2200</td>
<td>2200</td>
<td>200</td>
<td>450</td>
<td>280</td>
</tr>
<tr>
<td>10</td>
<td>2200</td>
<td>2200</td>
<td>200</td>
<td>450</td>
<td>250</td>
</tr>
<tr>
<td>10**</td>
<td>2200</td>
<td>2200</td>
<td>200</td>
<td>450</td>
<td>250</td>
</tr>
<tr>
<td>11</td>
<td>2200</td>
<td>2240</td>
<td>200</td>
<td>450</td>
<td>250</td>
</tr>
<tr>
<td>12</td>
<td>2200</td>
<td>22150</td>
<td>200</td>
<td>450</td>
<td>183</td>
</tr>
<tr>
<td>13</td>
<td>2240</td>
<td>2240</td>
<td>100</td>
<td>400</td>
<td>245</td>
</tr>
</tbody>
</table>

1* These values are ignored in graphs because of a change in operating conditions.
10** Taken one day later than Run No. 10.
exponential behaviour in the wings strongly suggests that this is the source of the difficulty. High counting rates could lead to faulty data due to inadequate recovery of voltages in the limiter, the photomultiplier voltage chain or the slow channel analyzers. Further experimental work is required before the source of the trouble can be isolated.

Fig. 4.11 shows the effects on the prompt curve of varying the \( \gamma \) photomultiplier voltage. From Fig. 4.11a it is seen that a 1% change in the high voltage causes a shift in the centroid position of 1.5 channels. The power supply used (J. Fluke, Model 413A) has a quoted stability of \( \pm 0.03\% \) per day. Assuming the \( \beta \) channel response to be similar, this variation in voltage would result in an uncertainty in the channel number of \( \pm 0.1 \), a negligible result in our experiments.

Fig. 4.11b shows the change in \( \omega_{1/2} \) for runs taken at different constant values of the \( \gamma \) photomultiplier voltage. Effectively this curve shows the result of using fewer photoelectrons in the timing mechanism. It would appear that some improvement could still be expected by working with even fewer photoelectrons. This could be accomplished by using higher photomultiplier voltages.

The effect on the centroid position of the energy dissipated in the crystals can be seen in Fig. 4.12. A constant energy width of 25\% was selected in the \( \gamma \) channel. Holding the \( \beta \) channel fixed, the mean \( \gamma \) energy selected was then varied. As this mean energy decreased the centroid shifted to higher channel numbers (Fig. 4.12a), in keeping with the
Fig. 4.11. Response to Variations in Ψ P.M. Voltage.

Fig. 4.12. Response to Variations in Energy Selection.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
fact that the $\beta$ pulse was delayed relative to the $\gamma$ pulse. That the corresponding result for the variation in the mean $\beta$ energy selected is much smaller is due to the $\beta$ spectrum (Fig. 4.13a) being much more strongly peaked than the $\gamma$ spectrum (Fig. 4.13b).

D. Conclusions

Under test conditions the converter and associated circuits have been shown to have a well defined linear region for 10 nsec. The electrical circuits are capable of resolving times of $2 \times 10^{-11}$ seconds.

The prompt curves obtained using a Au$^{198}$ source had a half width of $\sim 0.8$ nsec. and a slope in the wings corresponding to a half-life of $\sim 2 \times 10^{-10}$ seconds. These characteristics would allow us to measure lifetimes of 1 nsec. However some difficulty associated with high count rates will have to be corrected.

The overall efficiency of the experiment is limited by the low efficiency of the $\gamma$ detection. Some improvement could be expected by using a greater geometric compactness, a more efficient light reflector for the plastic scintillator, and possibly a larger scintillator.

With the same end in view it is suggested that some type of compensator circuit which would counteract the centroid channel shift due to various energies lost in the crystal could be designed using the information in Figures 4.12. This would allow the use of larger $\gamma$ energy windows.
Due to Compton scattered γ's.

Lens focussed on 412 kev β's.

Fig. 4.13. Energy Response of Scintillators.
(a) Beta Detector.
(b) Gamma Detector.
and hence increase the single channel count rate.

The results also suggest that we have not yet achieved the best timing mechanism. Some improvement could be obtained by working at higher photomultiplier voltages but a change to a semiconductor limiter circuit, which would require a smaller portion of the photomultiplier pulse to fire it, would probably yield better results.
REFERENCES


VITA AUCTORIS

Place and Date of Birth: Montreal, Quebec; December 16, 1939.

Education:

1959: Senior Matriculation
       Christian Brothers' College, Scarborough, Ontario.

1963: Bachelor of Science (Honours Physics and Chemistry)
       Assumption University of Windsor, Windsor, Ontario.

1963: Entered Faculty of Graduate Studies, University of
       Windsor (formerly Assumption University of Windsor),
       to proceed toward the Master of Science Degree in
       Physics.

Awards:


Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.