Eur. J. Phys. 15 (1994) 49–52. Printed in the UK

'Speed of light' measurement using BaF_2 scintillation detectors

Lee Chow, Stephen Lukacs and Kent Hopkins

Department of Physics, University of Central Florida, Orlando, FL 32816, USA

Received 24 May 1993, in final form 4 November 1993

Abstract. State-of-the-art timing technique is used to determine the 'speed of light' in an upper level undergraduate laboratory experiment. In this experiment we use the correlated 511 keV photons from positron annihilation obtained from a 100 μCi Na-22 source. The photons were detected by two BaF_2 scintillation detectors and, after careful time calibration of the entire counting system, the prompt coincidence peaks were each recorded as a function of the position of one of the detectors. As a result, the 'speed of light' was determined to be $3.002(16) \times 10^{10}$ cm s^{-1}, which is very close to the defined value of 2.99792×10^{10} cm s^{-1}. This experiment demonstrates the utilization of various nuclear instrumentation and timing equipment.

Zusammenfassung. Neuere Techniken aus der nuklearen Elektronik mit hoher Zeitauflösung werden zur Bestimmung der Lichtgeschwindigkeit in einem Experiment für das Fortgeschrittenen Praktikum angewandt. In dem Versuch werden korrelierte 511 keV γ-Quanten benutzt, die durch Positronen Vernichtung in einer 100 μCi ^{22}Na Quelle erzeugt werden. Die Photonen werden mit zwei BaF_2 Szintillationszählern detektiert. Nach einer sorgfältigen Zeit Eichung des gesamten Systems werden die Koinzidenz Linien der prompten γ-Quanten als Funktion des Abstandes der Detektoren bestimmt. Die Lichtgeschwindigkeit ergibt sich daraus zu $3.002(15) \times 10^8$ m s^{-1}, in guter Übereinstimmung mit dem exakten Wert von 2.99792×10^8 m s^{-1}. Der Versuch dient zur Demonstration von Instrumenten und Methoden der Zeitmessung aus der nuklearen Elektronik.

1. Introduction

In 1983, the International Committee on Weights and Measurements redefined the metre as '*the length of the path travelled by light in vacuum during a time interval of 1/299 799 458 of a second*' [1–3]. One important consequence of this new definition is that the value of the 'speed of light' becomes conventionally fixed and exactly equal to 299 792 458 m s^{-1}. So any attempt to measure the 'speed of light' will be a measurement of the length. Although the 'speed of light' is no longer a quantity that can be measured, the 'speed of light' measurement has remained a fascinating and instructive laboratory project for the undergraduate physics students. Various techniques and instrumentation have been used in the past to determine the 'speed of light' in the undergraduate laboratory. These include rotating mirror [4, 5], spectrometric [6–8] and nuclear time-of-flight [9, 10] measurements. Among these different techniques, the time-of-flight measurement is the most intuitive way of demonstrating the swiftness and finite nature of the speed of light. In a recent effort to upgrade our undergraduate nuclear spectroscopy laboratory, we purchased additional state-of-the-art nuclear instrumentation and realized that the 'speed of light' experiment could be carried out easily and with high precision in an undergraduate laboratory. In the following we will describe the experiment in detail.

2. Experimental details

This experiment was derived from one in which the student was required to measure the time resolution of BaF_2 scintillation detectors with the slow–fast technique. The slow–fast technique is a standard coincidence technique which uses two channels to process information. The timing signals from the anode go through the fast channel which consists of a discriminator and a time-to-amplitude converter. The energies of the photon are selected at the slow channel which consists of preamplifier, amplifier, single channel analyser and coincidence module. A schematic diagram of the experimental set-up using the slow–fast technique is shown in figure 1. We used a 100 μCi Na-22 source as our 'light source' and, since positron annihilation produces two correlated 511 keV photons at 180° angle, the coincidence counting rate was greatly enhanced. The source was sandwiched between two lead bricks with an exit

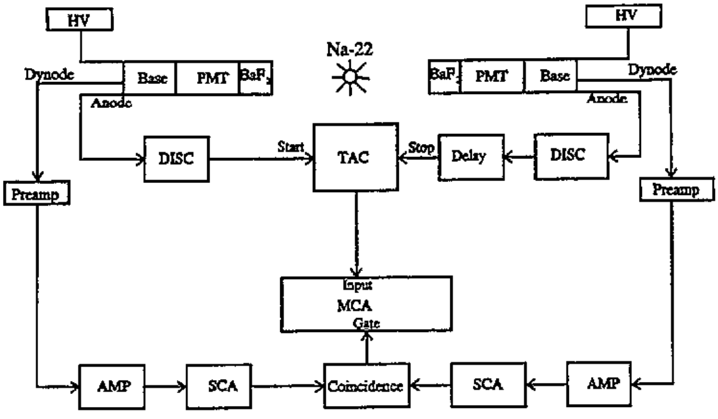


Figure 1. Schematic diagram of the experimental set-up using the slow–fast technique. The dynode signals pass through the slow channel which consists of preamplifier, amplifier, single channel analyser and coincidence module. The anode signals pass through the fast channel which consists of discriminator and time-to-amplitude converter. The arrows in the figure indicate the direction in which the signal travelled.

angle of 2°. The 1 in × 1 in BaF_2 scintillation crystal coupled with a Hamamatsu R2905 photomultiplier was purchased from Harshaw/Filtrol at a cost of $2710.

The BaF_2 scintillator was developed in recent years [11–15] to become an important instrument in the perturbed angular correlation and positron annihilation experiments. The light output from the BaF_2 scintillator has two components, one at 310 nm with a decay constant of 620 ns and the other at 225 nm with a decay constant of 0.6 ns. Although the fast component has only a 4% counting efficiency as compared with the NaI(Tl) scintillator, the excellent timing characteristic of this fast component more than compensates for the inefficiency in the counting rate. The Hamamatsu R2905 photomultiplier has a typical rise time of 1.3 ns and a transit time spread of 0.55 ns.

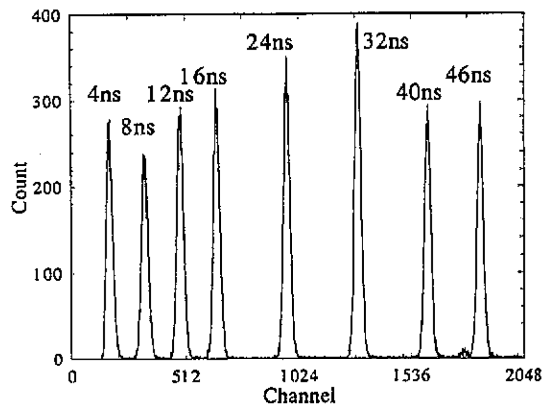
At the fast channel the anode signal was connected to a constant fraction discriminator (EG&G model 583 or equivalent); since the 511 keV photon is relatively easy to detect, the discriminator threshold was set at about the 50 mV level. The output of the discriminator was then fed to the start and stop of the time-to-amplitude converter (TAC) with the range of the TAC set at 50 ns. The output of the TAC was then connected to the input of a 2048-channel multichannel analyser (MCA). At the slow channel the 10th dynode signal was fed to the preamplifier and then to the amplifier. The output of the amplifier was fed to the single channel analyser (SCA) with the window set for the 511 keV photons. These SCA logic pulses were fed to a universal coincidence logic unit and the output of the coincidence was used to gate the MCA as shown in figure 1.

The pulse height spectrum taken this way defined the time resolution of the counting system at 511 keV. We determine the time resolution of our system to be 0.78 ns at 511 keV. To determine the time calibration of the system we used a nanosecond delay at the stop signal. The spectra with different delay times are shown in figure 2. The position of each peak versus the delay time was fitted to a linear function to obtain the time calibration of the system. Using this procedure, we obtained a time calibration of 0.024 845(63) ns/channel. The result is shown in figure 3.

3. Results

After determination of the time calibration of the counting system, a metre stick was taped down on the table and the stop detector was moved along

Figure 2. Coincidence timing spectra for different values of delay time.



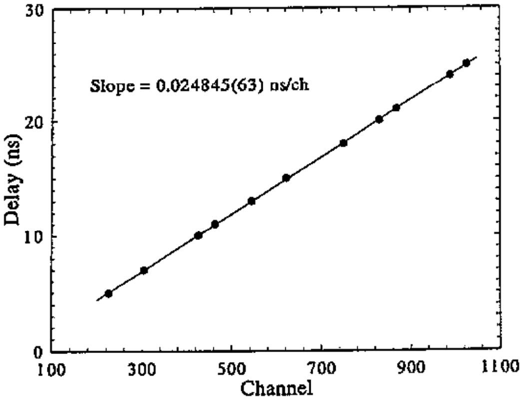


Figure 3. Time calibration of our counting system.

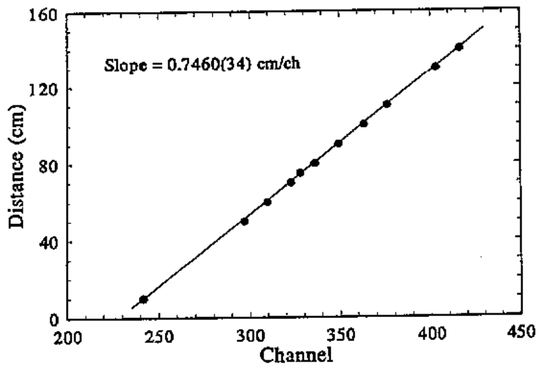


Figure 4. The displacement of the detector versus the peak channel number.

the metre stick while the prompt coincidence peak was recorded as a function of distance. Each coincidence spectrum took about 4 h and with a peak counts ranged from 15 000/channel to 400/channel depending on the distance of the two detectors. Eleven coincidence spectra were taken for distances between 10 cm and 140 cm. The peak positions were obtained using MAESTRO II software by EG&G ORTEC. The numerical values for distance of counter versus the channel number are listed in table 1 and are shown graphically in figure 4. The slope of distance versus channels was obtained by fitting the distance to the peak position. We obtained a slope of 0.7460(34) cm/channel. Using the time calibration of the system, 0.024 845(63) ns/channel, we obtained a speed of light to be $3.002(16) \times 10^{10}$ cm s^{-1}.

4. Discussion and conclusion

The errors in this experiment come from several sources. These include: (1) the finite extent of the sensitive volume of the BaF_2 phosphor, (2) the size of the Na-22 source, (3) the jitter in the rise-time and the transit time spread of the photomultiplier, (4) the linearity of various electronics used in the experiment including nanosecond delay, fast discriminator, time-to-amplitude converter and multichannel analyser and (5) the accuracy of the length measurement. The first four sources of errors combine together and manifest themselves in the time resolution of the coincidence peak, which is about 0.78 ns. This is the full-width-at-half-maximum value of the peak in a given coincidence spectrum. The peak in the coincidence spectrum has a Gaussian lineshape, which reaffirms that these sources of error are indeed random statistical errors. The position of each coincidence peak can be fitted with a non-linear least squares fitting program with an accuracy of 0.05 channel, which corresponds to 2.5 ps. We want to emphasize that the errors in the peak position are statistical errors which has been properly handled by the fitting program. From these, we obtained a percentage error of 0.3% for our time calibration (see figure 3).

Table 1.

Position	ΔL (cm)	Channel
1	10.0(1)	241.62(5)
2	50.0(1)	297.01(5)
3	60.0(1)	309.71(5)
4	70.0(1)	322.84(5)
5	75.0(1)	327.89(5)
6	80.0(1)	336.18(5)
7	90.0(1)	349.24(5)
8	100.0(1)	363.41(5)
9	110.0(1)	376.09(5)
10	130.0(1)	403.10(5)
11	140.0(1)	416.30(5)

The error in the distance measurement manifested itself in the coincidence measurements as a function of distance. We note here that the actual distance between the two detectors is irrelevant because it is the relative distance between each measurement which is important here. The fit to the data in table 1 gives us a percentage error of 0.45%. The combination of the two slopes in figures 3 and 4 gives us an overall error of 0.5% on the value of the 'speed of light'.

In this experiment the students learned basic timing techniques used in nuclear spectroscopy. They also acquired hands-on experience with fast scintillation detectors, constant fraction discriminators, time-to-amplitude converters, multichannel analysers and data analysis.

An important practical advantage of this experiment is that the whole experiment can be carried out on a laboratory table instead of using a light path of 30 to 180 m (typical for other time-of-flight measurements). This is due to the superior time resolution of the detectors used in our experiment. Recent improvements in nuclear instrumentation, especially

BaF_2 detectors, now make it possible to perform the classic 'speed-of-light' experiment in an undergraduate laboratory on a laboratory table.

Acknowledgements

This project is supported in part by the National Science Foundation's Instrumentation and Laboratory Improvement Program through grant #USE-9051765.

References

[1] Giacomo P 1984 News from the BIPM *Metrologia* **20** 25–30
[2] Bates H E 1988 Resource Letter RMSL-1: Recent measurements of the speed of light and the redefinition of the meter *Am. J. Phys.* **56** 682–7
[3] Giacomo P 1984 The new definition of the meter *Am. J. Phys.* **52** 607–13
[4] Dillman L T 1964 Improvement in measurement of the speed of light *Am. J. Phys.* **32** 567
[5] Domkowski A J, Richardson C B and Rowbotham N 1972 Measurement of the speed of light *Am. J. Phys.* **40** 910–2
[6] Palmer C H and Spratt G S 1954 A laboratory experiment on the velocity of light *Am. J. Phys.* **22** 481–5
[7] Rogers J, McMillan R, Pickett R and Anderson R 1969 A determination of the speed of light by the phase-shift method *Am. J. Phys.* **37** 816–22
[8] Page D N and Geilker C D 1972 Measuring the speed of light with a laser and pockels cell *Am. J. Phys.* **40** 86–8
[9] Huang W F 1970 Speed of light measurement *Am. J. Phys.* **38** 1159–60
[10] Sherbini S S 1980 Measurement of the speed of light using nuclear timing techniques *Am. J. Phys.* **48** 578–9
[11] Karwowski H J, Komisarcik K, Foster C, Pitts K and Utts B 1986 Properties of BGO and BaF_2 detectors *Nucl. Instrum. Methods* A **245** 207–8
[12] Wisshak K, Kappeler F and Muller H 1986 Prototype crystals for Karlsruhe 4π barium fluoride detector *Nucl. Instrum. Methods* A **251** 101–7
[13] Wisshak K, Guber K and Kappeler F 1987 Gamma-ray spectroscopy with a cooled barium fluoride crystal *Nucl. Instrum. Methods* A **259** 583–5
[14] Laval M, Moszynski M, Allemand R, Cormoreche E, Guinet P, Odru R and Vacher J 1983 Barium fluoride—inorganic scintillation for subnanosecond timing *Nucl. Instrum. Methods* **208** 169–76
[15] Hohenemser C and Schuhmann R B 1986 Simultaneous energy and timing decisions in time differential perturbed angular correlation experiments using BaF_2 scintillators *Hyperfine Interactions* **30** 109–19