HIGH EFFICIENCY DETECTORS FOR TIME-OF-FLIGHT WITH HIGH ENERGY NEUTRONS

C. D. Goodman
Oak Ridge National Laboratory,* Oak Ridge, TN 37830

J. Rapaport and D. E. Bainum
Ohio University,† Athens, OH 45701

M. B. Greenfield and C. A. Goulding
Florida A & M University,† Tallahassee, FL 32307

9506595
CONF-771023--10

Abstract

We discuss our experience in achieving sub-nanosecond time resolution with neutrons about 100 MeV on a scintillation detector 15 x 15 x 100 cm viewed by a single phototube. Time compensation is accomplished by tilting the scintillator axis with respect to the neutron flight path as discussed in a previous paper.[1] We also discuss the interplay between the time compensation from the geometry of light collection and the electronic technique for picking off the time signal.

Introduction

The design of neutron detectors generally involves making compromises between two opposing desires: On the one hand one wants to make the detectors large to increase counting efficiency, but on the other hand one wants to make detectors small to improve time resolution.

The relationship between size and counting efficiency is simple: To a first approximation the counting rate is proportional to the scintillator volume. The relationship between size and time resolution is, even to a first approximation, much more complicated. *In fact, in a previous paper*[1] it is shown that one can circumvent the simple notion that the spread in transit times ought to be proportional to some linear dimension of the scintillator.

The scheme is shown on fig. 1 taken from that paper. The axis of the scintillator is tilted so that the sum of the neutron and photon transit times is nearly independent of the position at which the scintillation occurs. Tests with 26 MeV neutrons on a scintillator 3.8 x 3.8 x 46 cm showed that good time compensation is possible, and sub-nanosecond resolution was realized.

We have now built larger detectors, 15 x 15 x 100 cm, and have used them for data taking in (p,n) reaction experiments at the Indiana University Cyclotron Facility. We report our experience with these larger detectors at neutron energies around 100 MeV in this paper.

Geometric Aspects of Time Compensation

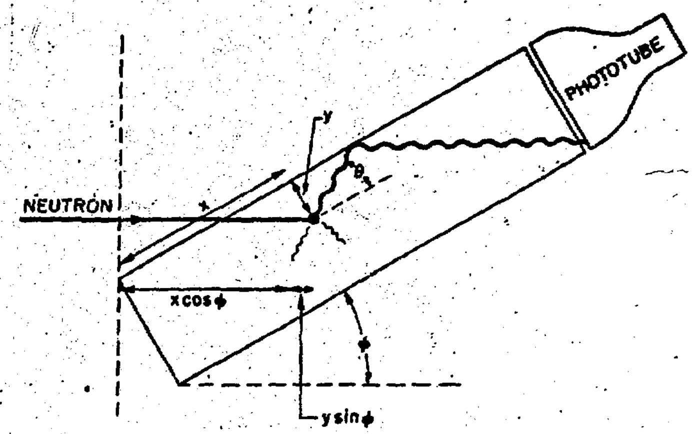
As can be seen from fig. 1, the time of arrival of a photon at the phototube from a scintillation occurring at coordinates x,y in the scintillator is

$$t(x,y,\beta,\theta) = t_o + \frac{nL}{c\cos\theta} + \frac{x}{c}\left(\frac{\cos\phi}{\beta} - \frac{n}{\cos\theta}\right) + \frac{y\sin\phi}{c\beta} \quad (1)$$

where t_o is the neutron time of flight up to the scintillator and the other variables are defined in fig. 1.

*Operated by Union Carbide Corporation for the Department of Energy.
†Work supported in part by NSF.

ORNL-DWG 77-7035



$$t_n = \frac{(x\cos\phi + y\sin\phi)}{\beta c} \qquad t_p = \frac{n(L-x)}{c\cos\theta}$$

Fig. 1. This figure shows the geometrical parameters of time compensation. β is the ratio of neutron velocity to the velocity of light. c is the velocity of light. n is the index of refraction of the scintillator. t_n is the transit time of the neutron and t_p is the transit time of the light (photon). L is the length of the scintillator.

What we wish to achieve by time compensation is to make t nearly independent of x and y for a given neutron energy, i.e., a given value of β. We assume that the light is emitted isotropically. We also do not use a reflector outside the scintillator so that light emitted with θ larger than the limiting angle for total reflection is lost. For an index of refraction n = 1.58, $\theta_{max} = 51°$. Thus, the time equation tells us that light from an instantaneous flash will arrive at the phototube over a period from $t(x,y,\beta,\theta = 0)$ to $t(x,y,\beta,\theta = 51°)$.

The total amount of light that has reached the phototube by time $t(x,y,\beta,\theta)$ is the amount of light emitted in the cone of half-angle θ. Examples of integral light curves are shown in fig. 2. The effect of the tilt angle ϕ is to displace the abscissa positions of these curves relative to each other. To first order, then, one would expect to achieve time compensation by choosing ϕ so that the curves cross at some point appropriate for the triggering criterion of the electronic circuit used for timing.

In a real scintillator the light is not emitted instantaneously. Rather it follows a curve of exponential decay with a characteristic decay time, e.g., 2.4 ns for the NE102 scintillator that we used. In addition the recoil proton stopping time becomes non-negligible above about 100 MeV. These effects cause the light curves to look like those in fig. 3. A

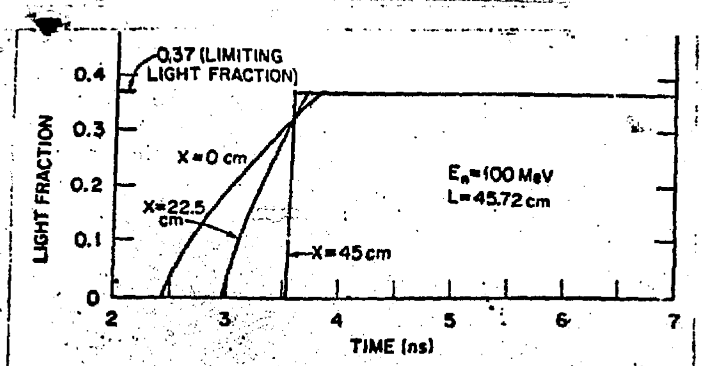


Fig. 2. These curves show the fraction of emitted light that has reached the phototube by time t for an instantaneous light flash at position x. The limit, 0.37, corresponds to a 51° collection cone.

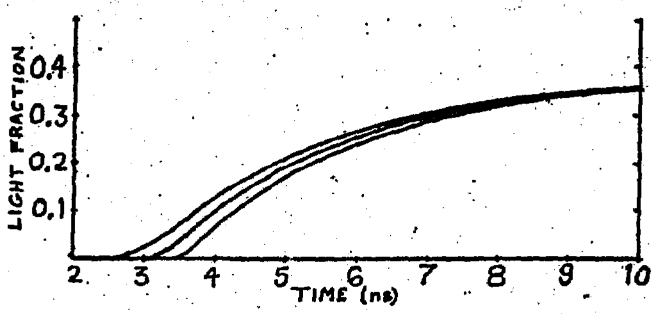


Fig. 3. These curves are those of fig. 2 with the decay time of the phosphor folded in.

more detailed discussion of the proton stopping is given in ref. 1. At 100 MeV the scintillator decay time is the dominant effect in determining the light curve.

Time Compensation Strategies

The light curves in fig. 3 are characterized by varying rise times as well as varying amplitudes (due to the random scattering angle in the neutron reaction). Constant fraction timing does not compensate for variations in rise time. An alternative strategy is to use a form of extrapolated zero timing.

We use two discriminators set at different thresholds on the output of the phototube. Assume the pulse shape is represented by a function of time, $f(t)$, and the pulse begins at $t = 0$. At time t_1, $f(t)$ reaches the first threshold amplitude, and at the t_2 it reaches the second threshold. If the functional form $f(t)$ is simple enough, we might be able to establish the time origin from a knowledge of t_1, t_2 and the corresponding threshold values.

Time correction is particularly simple if we can choose the threshold levels so that the time between the first and second threshold crossings is equal to the time from the beginning of the pulse to the first crossing. We set up a time-to-amplitude converter (TAC) to measure t_1 and another TAC to measure t_2-t_1. Then subtracting the output of the second TAC from the first corrects t_1 to be the true origin time.

The timing signal is then

$$T = t_1 - (t_2 - t_1) \qquad (2)$$

Let L be the threshold ratio,

$$f(t_2) = L\, f(t_1) \qquad (3)$$

(This form differs slightly from that used in ref. 1 because we have found it more convenient to vary thresholds than to vary TAC gains.) We can hope to use this form of correction if we can find a value of L that makes $T = 0$ with the appropriate form for $f(t)$.

We find from an inspection of the pulses on an oscilloscope that the function

$$f(t) = A[1 - \cos(t/\tau)] \qquad (4)$$

is a reasonable approximation of the leading edge of the pulse. Both A and τ vary. The small angle approximation of this is

$$f(t) \approx A(t/\tau)^2 \qquad (5)$$

Combining (2), (3), and (5) we find that $L = 4$ would compensate for variations in both A and τ.

Thus, if (5) is a valid approximation to the portion of the pulse sensed by the discriminators, we should choose the tilt angle to line up the origins of the pulses and use extrapolated zero timing with $L = 4$.

Experiments

We have constructed two detectors 15 x 15 x 100 cm each. The scintillator is made up of six slabs 2.5 x 15 x 100 cm coupled by a tapered light pipe to an RCA 4522 phototube. The electronic block diagram is shown in fig. 4.

We have used these detectors for obtaining neutron spectra from (p,n) reactions at the Indiana University Cyclotron Facility.

In most of the spectra the time resolution is approximately 1 ns, a portion of which is due to phase drifts of the cyclotron beam. The best resolution we have seen is about 0.8 ns FWHM. It was necessary to compensate for the cyclotron phase drift effect to observe this resolution.

A convenient way to state the efficiency of this kind of detector is as a percent of the end-on cross sectional area. With the detector axis oriented parallel to the flight path, the efficiency is the fraction of the neutron flux crossing the end area that produces detector signals. When the detector is tilted, we still express the efficiency with respect to the end area. This number can in principle become greater than 100%, but since the probability of a neutron interacting as it traverses the short dimension is small, in practice the efficiency is less than 100%. Of course it depends on the energy threshold, the neutron energy and the tilt angle. It is usually necessary to set the threshold high, perhaps one quarter to one half of the maximum neutron energy because the flight time of neutrons at that fraction of the energy becomes greater than the separation of beam pulses, and the time spectra from adjacent bursts would overlap if the threshold were set lower. With typical constraints, the efficiency is of the order of 30%.

A neutron spectrum obtained from $^9Be(p,n)^9B$ is shown in fig. 5.

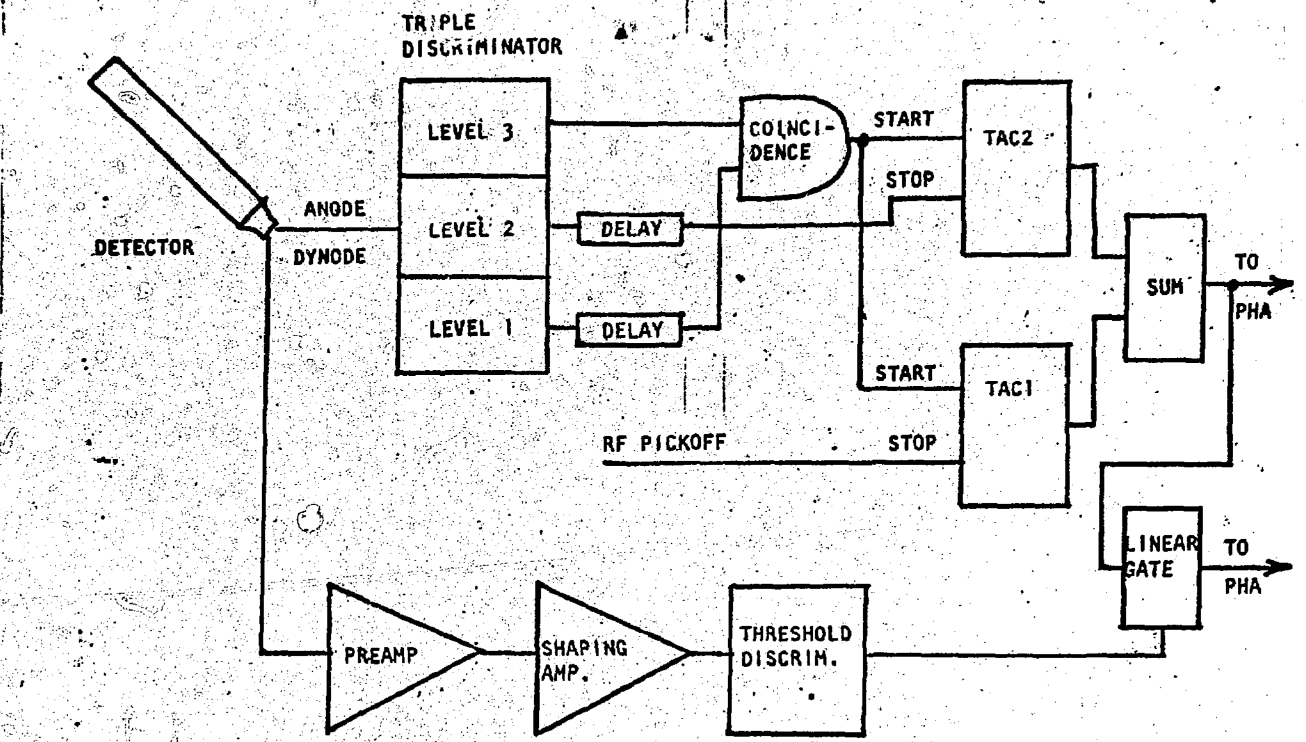
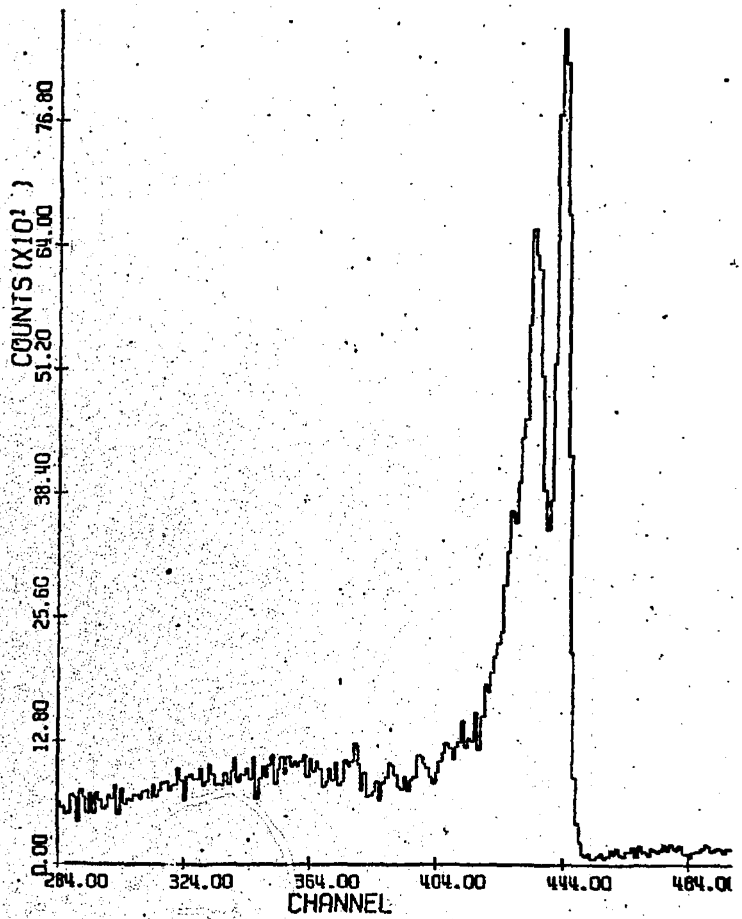


Fig. 4. Block diagram of electronics as used for data taking in the (p,n) experiment.

Fig. 5. A time spectrum from $^9Be(p,n)^9B$, with 120 MeV protons. The time resolution is between 0.8 and 0.9 ns FWHM.



Retrospective Analysis of Performance

A small portion of the experiment time was taken to study the effects of varying the tilt angle and the timing thresholds. We found that the best resolution occurred with a tilt angle smaller than that required to cancel the x dependence in eq. (1) for the axial light rays. For example, with 117 MeV neutrons the time spread cancellation for longitudinal position occurs for $\phi = 43°$. The best compromise for minimizing longitudinal and transverse position effects is approximately $\phi = 35°$, giving a total calculated time spread of about 0.7 ns. We obtained the best resolution, 0.8 ns, at $\phi = 18°$. It is difficult to get consistently reproducible results because the overall resolution is made up of roughly equal contributions from cyclotron phase drifts and detector effects. Nevertheless, the trend of finding the best resolution at tilt angles smaller than the angles calculated from geometry alone seems definite.

We tentatively attribute this to a slope dependence of the discriminator triggering time. At smaller tilt angles, the slower rising pulses are moved to an earlier time with respect to the fast rising pulses (see fig. 2). If the discriminator responds more rapidly to a faster rising pulse, then one can use the tilt angle to compensate for the discriminator characteristics and obtain better resolution than one would calculate for the same operating conditions using the simple arguments.

The best value of threshold ratio, L in eq. (3), seemed to be about $L = 10$. This suggests that the pulses are not simply parabolic as we assumed in the simplified analysis. The best L value might also be affected by the discriminator triggering characteristics.

We obtained additional information by setting up a 1 meter long scintillator with axis parallel to the flight path and a phototube at each end. The simultaneous time signals from the two ends were recorded in a two parameter array. The timing was done as described above with $L = 10$.

In this mode the back phototube gives a partly compensated time spectrum while the front tube gives a spectrum in which the position dependent time spreading is exaggerated. The time difference gives a measure of the position at which the scintillation occurred.

In these data the front-back time difference seen by the back phototube appears to be barely over 1 ns instead of the 2 ns calculated value. Unfortunately, the data taking grid was too coarse to make a precise determination but this is consistent with our observation that the best resolution is obtained at smaller tilt angles than calculated from the simple model. One also sees the attenuation of neutrons by the scintillator. The number of events near the back is roughly 30% less than the number near the front. Again the data were too crude to obtain a precise number. The method, however, is a valid technique for measuring the efficiency of the detector over the entire energy spectrum in one experiment. The front to back attenuation for any portion of the spectrum is the detector efficiency at that energy. With a phototube at each end and axis parallel to the flight path, the detector can be used to measure its own efficiency. It is also possible that sufficient position information could be obtained from the pulse rise time to measure the efficiency with only one phototube.

Comparison with Other Methods of Using Large Scintillators

We have stressed the technique of using a single phototube on a large scintillator. Other experimenters have previously achieved large scintillator volumes by 1) using many small scintillators,[2] 2) using a transverse scintillator with two phototubes and mean timing,[3] and 3) using a longitudinal scintillator with two phototubes and a special timing technique.[4]

With respect to multiple small detectors, our results show that the individual detectors can be very large.

With respect to the other techniques one can make comparisons showing the advantages and drawbacks of using a scintillator in a transverse, parallel or tilted orientation relative to the flight path. The information in eq. (1) covers all these conditions.

With a transverse scintillator one must use a phototube at each end and one compensates for the photon transit time spread by electronically taking the mean time. The rise times of the pulses seen by either tube vary according to the distance to the scintillation but a fast rising pulse at one end goes with a slow rising pulse at the other end and the effect tends to cancel out. The main drawback of a transverse scintillator is that it must be thin in the direction of the forward scattered proton recoils. At 100 MeV, for example, the proton range is 7.5 cm. A detector 7.5 cm thick already gives a time spread of .58 ns. One would really like to make the detector several ranges thick so that most of the protons deposit most of their energy.

If the detector axis is parallel to the flight path the thickness is used to best advantage with respect to the proton recoils. The time dispersion due to transverse thickness, the y term in eq. (1), is exactly zero. One then needs to compensate for the x time dispersion. With two phototubes this has been done with analog circuitry[4] and can be done also by appropriate processing of the two timing signals as our results here show. A disadvantage of the technique is that a phototube, base, and light pipe are placed in the neutron path, and for precise measurements the neutron attenuation in these objects must be known, and the data corrected accordingly.

We think that one could compensate a longitudinal detector with a single phototube by making use of the rise time information from the back tube. Note also that when $\beta = 1/n$ the compensation occurs naturally. This corresponds to 274 MeV neutrons in NE 102 scintillator.

The tilted scintillator seems to us to be an attractive technique for which we have demonstrated that a single phototube suffices. The apparent drawback that the compensation is energy dependent is really not very harmful because the energy window is fairly large. For example, for a 1 m long detector tilted at 40° the timing spread due to the x terms in eq. (1) is less than 0.5 ns between 108 MeV and 173 MeV. In terms of energy resolution the window looks even wider because a given energy resolution corresponds to poorer time resolution at lower energy.

Conclusions

We have shown that a tilted scintillator viewed by a single phototube gives good results as a time-of-flight neutron detector. Our results indicate that further optimization of this scheme might be possible. We propose for ourselves further experiments in which we would record in event mode the threshold crossing times for the three discriminators, the pulse amplitude and the time from a phototube at the front end of the scintillator. From this information we can hope to deduce the optimum timing function.

Acknowledgements

We wish to thank Professor Richard Madey of Kent State University for lending us a 1 m long scintillator with phototubes at both ends for one of our tests. We also wish to thank Dr. Charles Foster and the staff at the Indiana University Cyclotron Facility for assisting in the set up and data taking and for providing a proton beam.

References

1. C. D. Goodman, J. Rapaport, D. E. Bainum, and C. E. Brient, to be published in Nucl. Instr. and Meth.

2. W. C. Parkinson, J. F. Petersen, R. H. Day, R. M. Polichar, P. F. Julien, and D. C. DuPlantis, Nucl. Instr. and Meth. 119, 51 (1974); D. A. Lind, R. F. Bentley, J. D. Carlson, S. D. Schery, and C. D. Zafiratos, Nucl. Instr. and Meth. 130, 93 (1975).

3. G. Charpak, L. Dick, and L. Feuvrais, Nucl. Instr. and Meth. 15, 323 (1962); C. Ward, A. Berick, E. Tagliaferri, and C. York, Nucl. Instr. and Meth. 30, 61, (1964); L. Paoluzi and R. Visentin, Nucl. Instr. and Meth. 65, 345 (1968); D. Evers, E. Spindler, P. Konrad, K. Rudolph, and W. Assmann, Nucl. Instr. and Meth. 124, 23 (1975).

4. J. D. Carlson, R. W. Finlay, and D. E. Bainum, to be published in Nucl. Instr. and Meth.