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A NEW PHOTOGRAPHIC METHOD FOR NEUTRON VELOCITY SPECTROGRAPHY (II)

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Synopsis

In a previous paper [1]) the principles were presented of a new and simple method for neutron velocity spectrography. In this second paper we give a more elaborate description of the apparatus and of some simple experiments to test its performance.

§ 1. *Introduction.* One of the chief drawbacks of high resolution neutron velocity spectrography has been the complexity of the necessary apparatus. By Milatz, Endt and Paris [1]) [2]) it has been shown that this difficulty can be largely overcome by the use of the "continuous photographic method", an extension of the photographic method first suggested by Milatz and ter Horst [3]).

Paper I contained only the principles of this new method which may be summarized as follows: every neutron detected by a suitable neutron detector e.g. BF_3-filled proportional counter causes a short lightflash on an oscillograph screen. The circular time-base of this oscillograph is synchronized to the repetition-rate of the pulsed neutron source. The screen is photographed on a fixed plate and the photographic densities on this plate are measured by means of a circular densitometer. These densities are interpreted into lightflash densities along the circle circumference by means of a calibration spectrum consisting of known flash densities diminishing exponentially along the circle circumference (paper I, Fig. 3).

In this paper II we shall present more instrumental detail and some simple experiments to test the performance of the apparatus. In § 2 we shall give a discription of the neutron detection equipment consisting of proportional counter, pulse amplifier, discriminator, scalers and pulse shaper circuit. In § 3 the timing equipment is given i.e. the apparatus for production of the circular time-base and the apparatus for the modulation of the neutron source. The neutron source proper is described in § 4. For a block-diagram showing the connections between these functional units we refer to paper I, Fig. 2. The camera and circular densitometer are dealt with in § 5, and § 6 contains a description of the equipment for the production of the exponential calibration spectrum. In § 7 the errors are estimated made in intensity measurements and in § 8 those in time of flight measurements.

In Fig. 1 a photograph is given of the electronic equipment on which also the camera can be seen fixed with screws to the front panel of the oscillograph.

§ 2. *Neutron detection equipment.* The apparatus for neutron detection and counting consists of:

a) boron-lined proportional counter;

b) pulse amplifier;

c) discriminator;

d) pulse shaper converting the output of the discriminator into rectangular pulses of controllable width to be fed to the oscillograph modulation grid;

e) scaler and mechanical register counting all pulses passed by the discriminator.

The proportional counter consisted of a cylindrical brass tube 5″ in diameter and 12″ long lined on the inside with borax and with 4 mil central tungsten wire. It was filled with air to a pressure of 20 mm Hg. At 1000 V the gas amplification factor amounted to about 20 to 50.

The pulse amplifier was of a design given by Elmore and Sands [4]) (Los Alamos Model-220) making use of eight 6AK5 tubes. The first serves as preamplifier (cathode follower) and is mounted on the proportional counter housing. The main amplifier consists of two feed-back loops each of three tubes and a cathode follower. The mid-band gain is 25,000. The pulses passed by the amplifier have a rise-time of 0.5 μs and a half-width of 5 μs.

The design of the discriminator was also taken from Elmore and Sands. It consists of a Schmitt trigger-circuit followed by a phase-reversal tube (all 6AK5). It delivers at the output negative pulses of constant amplitude (30 V) for all input pulses larger than some preset value, variable between 0 V and 100 V.

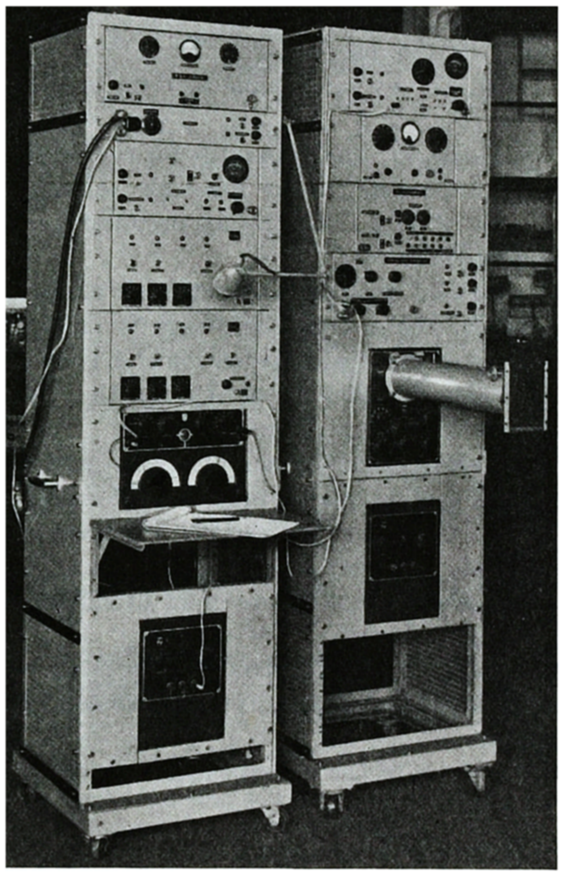

Fig. 1. Electronic equipment. The left-hand rack contains (from top to bottom): 2 kV power supply, pulse amplifier, discriminator and Poisson selector (in one chassis), two identical scalers (scaling ratio 16 : 1), oscillator and 300 V power supply. In the right-hand rack are mounted (also from top to bottom): pulser and pulse shaper I (in one chassis), 300 V power supply, pulse shaper II, circular time-base amplifier, oscillograph (with camera mounted on front panel), and 300 V power supply.

The pulse-shaper succeeding the discriminator delivers positive rectangular pulses of 120 V amplitude to the oscillograph modulation grid. It contains two 6SN7 tubes of which the first serves as a monostable multivibrator, the first half of the second tube as a blocking stage and the second half as a phase-reversal stage. The pulse-width at the output can be varied from 2 μs to 100 μs and the pulse rises resp. falls within 0.5 μs. The scalers used to count all pulses passed by the discriminator were of conventional design of 5 μs resolution. The overall scaling factor was 1024.

§ 3. *Timing equipment.* The apparatus for the production of the circular time-base consists of the following sub-units:

a) an oscillator (Philips GM 2307) for production of a sine-wave signal of good quality;

b) the "time-base modulator" to effect a slow alternate expansion and contraction of the circular time-base for reasons explained in paper I, § 2; it consists of a potentiometer connected by gear transmission to a synchronous motor of which the sense of rotation is reversed by a switch every 25 seconds;

c) a RC-phaseshift circuit to shift the sine-wave signal fed to the horizontal deflection plates of the oscillograph 90 degrees in respect to the signal fed to the vertical deflection plates;

d) two push-pull amplifiers (of which one is preceded by the phase-shifter) to provide sine-wave signals of sufficient amplitude to the two pairs of deflection plates;

e) an oscillograph (Philips GM 5652) with a DN 9–4 tube (useful diameter about 8 cm) for the transformation of electrical pulses into lightflashes.

The wiring diagram of the circuits listed under *b*), *c*) and *d*) is given in Fig. 2.

The input voltage taken from the oscillator is 5 V r.m.s., the output (between two deflection plates) 75 V, both for a 3″ circle diameter on the oscillograph screen. All circuits are designed to pass a wide range of frequencies; we normally used a repetition frequency of 1000 c/s. Potentiometer P_3 is the motordriven time-base modulator. Potentiometers P_1 and P_2 serve to adjust the modulation depth, normally about 15%. The EF6 tube succeeding the modulator feeds two signals from cathode and plate of equal amplitude and 180 degrees phase difference into the phase-shifter composed of potentiometer P_4 and capacitor C_1 (variable in steps). By means of potentiometer P_5 the amplitude of the signal to the vertical deflection plates can be adjusted. This serves to compensate for the unequal deflection sensitivities of the two pairs of deflection plates and for small differences in gain of the two amplifiers. To the output fed to the deflection plates is added a small controllable d.c. voltage by means of the potentiometers P_7 and P_8. Their adjustment enables to shift the center of the time-base circle into the center of the screen. The design of the circuits for the production of the circular time-base differs in principle not very much from that given by East and Standing[5]). For reasons of power economy we used EF6 tubes instead of their 6V6's.

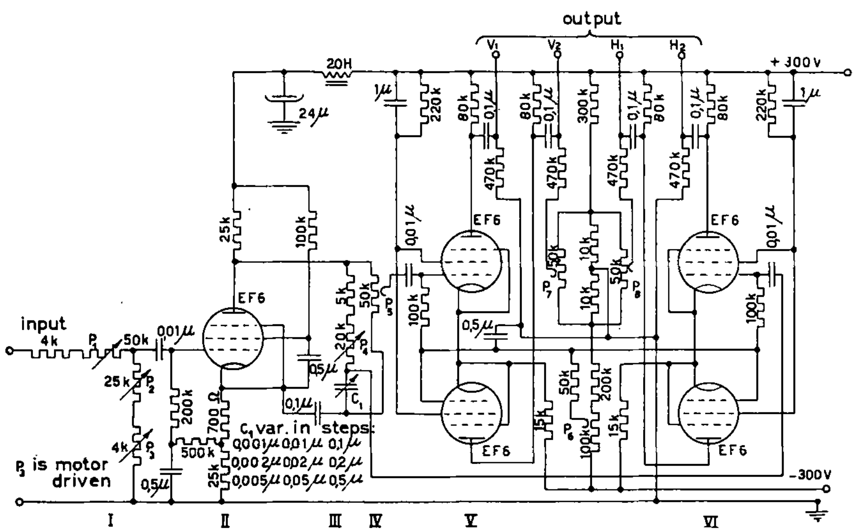

Fig. 2. Circular time-base. The sine-wave of the oscillator fed into the input passes the modulator circuit (I) and is then delivered to the phase-reversal tube (II). Between plate and cathode of this tube is connected the 90 degree phase-shift circuit producing the input signal for the horizontal amplifier (VI). The input signal for the vertical amplifier is taken from the attenuator (IV). The sine-waves at the output of the amplifier are fed to the deflection plates of the oscillograph.

Errors are introduced in time of flight measurements if the time-base contains harmonics. The harmonics content of the time-base can best be judged by making a photograph of the oscillograph screen and comparing the time-base to a perfect circle. It was found that the maximum deviation from a perfect circle amounted to 0.8%. It was also checked that the time-base once well adjusted does not lose its adjustment after some time by amplifier drift or similar causes. From two photographs one taken two hours after the other the second one did not show any measurable increase in the deviation from a perfect circle.

Besides the time-base apparatus described above the timing equipment also includes the circuits for the modulation of the neutron source. They convert the sine-wave 1000 c/s signal produced by the oscillator into a positive rectangular pulse of controllable width repeated at 1000 μs intervals. This is done in two steps.

In the first step (called the "pulser") consisting of four amplification stages (see Fig. 3) the oscillator sine-wave signal is converted into sharp pulses of 2 μs width repeated at 1000 μs intervals. The first three stages transform the sine-wave into a square wave, which is then differentiated by the small RC-constant between the third and fourth stage. From the resulting alternating positive and negative pulses the negatives are suppressed in the fourth stage.

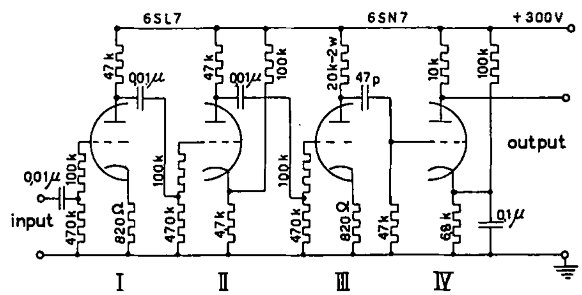

Fig. 3. The pulser. The oscillator sine-wave is first transformed into a square wave by the first three amplification stages and then differentiated. From the resulting sharp alternating positive and negative pulses the negatives are suppressed in the fourth stage.

The second step consists of a pulse shaper similar to the one described in § 2 transforming the pulses from the pulser into positive rectangular pulses of controllable width which modulate the ion source of the neutron generator.

§ 4. *Neutron generator.* Neutrons were produced by bombarding a heavy-ice target with 100 keV deuterons. The ion source was of the magnetic oscillating electron type [6]). In order to pulse the source the rectangular pulses from the ion source pulse shaper were fed to a grid mounted between cathode and anode of the ion source. This set-up eliminated the use of a power amplification stage between pulse shaper and ion source. Normal operating conditions of the source were: anode voltage 600 V, anode current 15 mA, magnetic field 300 Oersted, grid-swing from 0 V to —100 V, grid current (at —100 V) 100 μA, pressure in the source 2×10^{-3} mm Hg, gasconsumption 50 cc atm/hour. Under these conditions the ion current arriving at the target amounted to 400 μA (measured without magnetic analysis). Under optimum conditions the neutron yield was equivalent to 1 Curie Ra—Be.

§ 5. *Camera and circular densitometer.* The best way to photograph the oscillograph screen appeared to be the use of 1 : 1 magnification and 9 cm $\times$ 12 cm plates. This large photographic image makes for a simple construction of the circular densitometer obviating the use of two microscope objectives as in ordinary microdensitometers.

It was necessary to construct a special camera to be fixed with four screws on the oscillograph front panel. The camera (see Fig. 1) consisted of a brass tube in respect to which the lens ($1\frac{3}{4}''$ diameter, $5''$ focus) and the plate-holder could be moved so as to make it possible to change the magnification from 1 : 1 to 2 : 1. The positions of lens and plate-holder could be read on millimeter scales to obtain easy and reproducible focussing. It must be emphasized that the integrating property of the photographic plate obviates the necessity for high light efficiency of the system oscillograph screen-camera-photographic plate. It is not necessary that every lightflash on the screen causes a very black dot on the plate after development.

In the circular densitometer (Fig. 4) the plate fixed to a lucite plate-holder is rotated in its plane. It uses two lenses each of $4''$ focus and 1 : 1 magnification to focus the light from the entrance slit on the plate and to focus the light passed by the plate on a thermopile. The plate-holder is rotated by a small synchronous motor with gear transmission bringing down the speed to one revolution per four minutes. The deflections of the galvanometer connected to the thermopile are registered photographically.

§ 6. *Calibration of the plate.* In paper I § 3 the principles were presented of the system to provide a calibration spectrum of exponentially decreasing flash-density along the circle circumference on the oscillograph screen. The function of the circuit providing these calibration pulses is to select from a random pulse series the first pulse in every time-base period. The beginning of the time-base period is marked by the regularly spaced pulses from the pulser (see § 3).

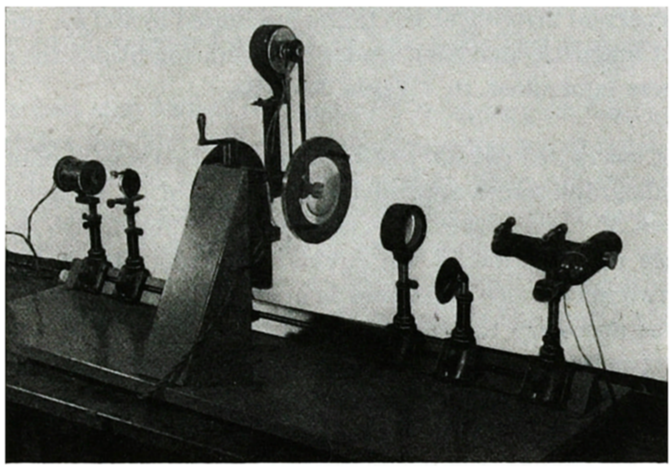

Fig. 4. Circular densitometer. From left to right: lamp, entrance slit, lens, photographic plate fixed to a rotating lucite plateholder, lens, thermopile.

The random pulses (at a rate of several thousand per second) needed for the calibration have to satisfy rather rigid requirements. A Geiger counter as a source of random pulses would be insuitable because of its long dead time. A multiplier tube however succeeded by the fast pulse amplifier and discriminator described in § 3 has a negligibly small dead time. The pulse rate can be varied with a small controllable light intensity on the photo-cathode but it is also possible to use the "dark current pulses" of which the rate can be varied by means of the discriminator setting. It proved very difficult however to eliminate long term fluctuations of the pulse rate, which should be smaller than 1%. Even excellent stabilization of the high voltage on the multiplier tube and of d.c. and a.c. supply to pulse amplifier and discriminator did not diminish the observed fluctuations of about 3%. This problem was solved quite satisfactorily by using the multiplier as a scintillation counter. In front of the photo-cathode a sodium iodide crystal was fixed irradiated with beta particles from a weak RaD source. The pulses produced are so large that small changes in gain of multiplier or amplifier or in the discriminator setting have only an insignificant influence on the pulse rate.

§ 7. *Errors in measurements of intensities.* In this paragraph the errors are discussed made in measurements of neutron intensities. In principle these errors can be introduced by a number of causes of which the most obvious are: 1. local differences in light emission of the oscillograph screen, 2. local differences of the sensitivity of the photographic plate, 3. statistical fluctuations of the number of lightflashes contributing to the photographic density on a small area of the plate, 4. graininess of the plate.

It can easily be shown that the last factor can be neglected. The size of the light spot used in the circular densitometer is 2 mm^2. On this area Ilford Selochrome plates, used throughout this work, contain about 7×10^5 developed grains if exposed to 50% transmission. This number is so large that the corresponding relative fluctuation can be disregarded safely.

An idea as to the order of magnitude of the first and second factors can be obtained by making a photograph of the circular time-base without any pulses on the oscillograph modulation grid and without suppression of the beam. The corresponding densitogram shows small deviations from a straight line amounting to 2% in transmission, the average transmission being 50%. Making use of the measured density-intensity relation for this plate it can be computed that this corresponds to 3% fluctuation in neutron intensity. If a second photograph is made it is found that the fluctuations on this plate are quite uncorrelated with those on the first. It follows that the light emission of the oscillograph screen can be regarded as uniform and that the fluctuations are caused by changes of the sensitivity over the surface of the plate. Thus the upper limit of the accuracy of intensity determinations is determined by these 3% fluctuations. At very low neutron intensities the statistical fluctuations, third cause of errors mentioned above, may predominate but they are of course not inherent to our method alone but to any neutron detecting system.

Finally the accuracy of intensity measurements is strongly dependent on the correct operation of the selector circuit producing the exponential calibration spectrum. To check this point two exposures were made on the same plate with different average time-base radii, and identical times of exposure, one exposure of the calibration spectrum and the other of a uniform intensity spectrum obtained by feeding random pulses of known pulse rate to the oscillograph modulation grid. This pulse rate was then compared to the pulse rate corresponding to that part of the calibration spectrum, which causes the same photographic density. The latter pulse rate was calculated from the random pulse rate fed into the selector circuit and from the phase of the calibration point in question by means of the exponential Poisson law given in I § 3. A small correction must be applied for dead time of the selector and scaling circuits (both 5 μs). In order to be able to compare densities of exposures made with different average time-base radii $\langle r \rangle_{Av}$ it is evident that also the width Δr of the time-base "band" (see I § 2) has to be different in such a way as to keep the area of the time-base band $2\pi \langle r \rangle_{Av} \Delta r$ constant.

From these checks it was found that measured pulse rates and those calculated from the calibration spectrum always agreed to within 3% which is as good as can be expected from the 3% sensitivity fluctuations over the surface of the plate mentioned above.

§ 8. *Resolving power.* It has been pointed out repeatedly that the resolving power for neutron velocity spectrometers is determined largely by the intensity of the neutron source available. Moreover resolving power is a function of neutron energy, decreasing generally with increasing energy. However instead of giving a thorough discussion of the many factors influencing resolving power we shall present here only a few points of interest to our particular method.

One factor determining the accuracy of time of flight measurements is the harmonics content of the circular time-base (see § 3). This error amounts to 1% of the repetition period. Another limit is set by the minimum pulse width of 2 μs to be obtained from the pulse shaper (see § 2). It depends on the repetition period which one of these two errors is the larger.

Apart from random timing errors there is also a constant delay between the beginning of the ion source "on-time" and the first lightflashes observed on the oscillograph screen due to neutrons registered by the proportional counter. This total delay is the sum of delays introduced by the acceleration tube, the proportional counter, the pulse amplifier, the discriminator and the pulse-shaper. It is measured generally by omitting any slowing-down medium (e.g. paraffin) round the target thus recording only fast neutrons. The intensity of our neutron source however was not large enough to apply this procedure. Instead the acceleration tube delay was measured separately by recording with a G.M. counter X-rays given off by the tube. The ion source was pulsed with square pulses of 5 μs width at a rate of 16.000/sec. The pulses from the counter were transformed by the pulse shaper into square pulses of 3 μs width and then fed to the modulation grid of an oscillograph with linear time-base synchronized to the ion source modulation frequency. The oscillograph anode tension was increased to 5 kV to obtain sufficient light output. The ion source modulation pulse was also fed to the vertical deflecting plates of the oscillograph. The delay measured in this way, from the front of the ion source modulation pulse to the front of the first G.M. pulse observed on the screen, amounted to 2.0 ± 0.5 μs. This is the sum of delays introduced by the acceleration tube, the G.M. counter (estimated as 0.5 ± 0.3 μs), and the pulse-shaper. As a conclusion the sum of acceleration tube and pulse-shaper delays can be given as 1.5 ± 0.6 μs. This compares favourably with delays found for cyclotrons which are generally about 5 μs to 10 μs. To obtain our total delay we still have to add delays of proportional counter, pulse amplifier and discriminator which are estimated as 1.0 ± 1.0 μs, 0.5 ± 0.5 μs and 0.5 ± 0.5 μs respectively. The total delay thus amounts to 3.5 ± 1.5 μs.

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REFERENCES

1) Milatz, Endt and Paris, Physica **16** (1950) 537 (referred to as Paper I).
2) Endt, P. M., Thesis Utrecht 1951.
3) Milatz, J. M. W. and ter Horst, D. Th. J., Physica **5** (1938) 796.
4) Elmore, W. C. and Sands, M., "Electronics", Mc Graw Hill, New York, 1949.
5) East, T. W. R. and Standing, A. F., J. sc. Instr. **26** (1949) 236.
6) Veenstra, P. C. and Milatz, J. M. W., Helv. phys. Acta **23** (1950) 39 and Physica **16** (1950) 528.