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COMMISSION OF THE EUROPEAN COMMUNITIES

INVESTIGATION OF SOME PROPERTIES OF THE PRECISION LONG COUNTER

by

O. P. MASSAND

1972

Joint Nuclear Research Centre
Geel Establishment - Belgium
Central Bureau for Nuclear Measurements - CBNM

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ABSTRACT

The Precision Long Counter (PLC) has been introduced by J. De Pangher in order to get a reproducible counter for neutron flux density measurements. This counter is believed to have the characteristics of a standard instrument. A combined order of thirteen PLC's for West European laboratories was organised from the Central Bureau for Nuclear Measurements and the present counter is one of them. An effort has been made to set up this PLC and to do its calibration with internal, external radioactive neutron sources and monoenergetic accelerator neutrons and to finally arrive at its energy response. This report describes some of the measurements carried out with this PLC.

KEYWORDS

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CALIBRATION
STANDARDS
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NEUTRONS
BF3 COUNTERS
FAST NEUTRONS
DISCRIMINATORS
PULSES

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Preface :

The Precision Long Counter (PLC) has been introduced by J. De Pangher in order to get a reproducible counter for neutron flux density measurements. This counter is believed to have the characteristics of a standard instrument. A combined order of thirteen PLC's for West European laboratories was organised from the Central Bureau for Nuclear Measurements and the present counter is one of them. An effort has been made to set up this PLC and to do its calibration with internal, external radioactive neutron sources and monoenergetic accelerator neutrons and to finally arrive at its energy response. This report describes some of the measurements carried out with this PLC.

Investigation of some properties of the Precision Long Counter

1. Introduction

The precision Long Counter (PLC) was developed by J. de Pangher (1) from the original Hanson-McKibben Long Counter (2) in order to get a reproducible counter for neutron flux density measurements. This counter is believed to have the characteristics of a standard instrument because a number of PLC's have been made from the design and found to be reproducible to better than 1% and as such its use is widely increasing. In Europe, the Twentieth Century Electronics Limited, New Addington, Croydon, Surrey has been chosen as a suitable manufacturer and these counters are subjected to some radiological tests - called contractual tests - at N.P.L., Teddington, England (3). A combined order of thirteen PLC's for West European laboratories was organized (4) and the present counter was delivered to us (Moderator Assembly No. ZK 1355). An effort has been made to set up this PLC and do its calibration with the internal Am-Be source, with external radioactive neutron sources and mono-energetic neutrons from the Van de Graaff accelerator to arrive at its energy response, so that it can be used as a secondary standard for measuring neutron flux density.

2. Description of the PLC

Figure 1 shows a sketch of the PLC. The description as to the design of the PLC can be found in (1). It essentially consists of a cylindrical moderator assembly of polyethylene with a BF_3 tube arranged along its axis. The whole is contained within an aluminium jacket to prevent destortion of the polyethylene. An internal source is provided for day to day calibration of the BF_3 tube. The main advantages of this counter as a standard for the measurement of neutron flux density are as follows :

(i) High efficiency for fast neutron detection.
(ii) Relatively uniform response to neutrons of different energies.
(iii) Excellent discrimination against gamma rays.
(iv) Good approximation to a point detector.

The first thing was to set up the counter. It has been mounted on a carrier (see fig. 2) fabricated in our workshop. The carrier provides the following facilities : a) the counter can be moved forward or backward by 50cm, b) it can be positioned at a height of 1m to 1.30m above the ground level. The carrier has movable wheels so that the counter can be easily moved from place to place. Once fixed at its middle with a pin it can be rotated around its geometrical centre.

Next thing was assembling the various electronic units. The pre-amplifier used had a fixed gain of 25 and contained a frequency band pass corresponding to 0.1 μs integration and 3 μs different-action time constants. It was constructed by Mr. Rousseau of C.B.N.M..

It is mounted on the PLC carrier (see fig. 2) and is directly coupled to the BF_3 tube. The threshold discriminator, scaler and timer units were obtained from the Electronics Group of C.B.N.M.. All these units have been put in one power supply chassis.

3. Calibration with the internal source

The internal source in our case is a small source of Am-Be obtained from Radiochemical Centre Amersham, with an emission rate of 7.2×10^4 neutrons/sec. It is loaded permanently in the source holder rod which accurately locates it within the PLC during its calibration (see fig. 1). Normally, a similar dummy rod without the source is inserted in this position. The BF_3 tube in our case is a copper tube 26 EB 25.38, from the 20th Century Electronics Ltd., with ^{10}B enriched BF_3 at 25 cm Hg pressure, 26 cm active length and 38 mm diameter. Its resolution remains practically unaffected and per cent changes in the counting rate during the exposure period are also very small (1). The tube has a plateau region of about 350 V (see fig. 3). Fig. 4 shows the output pulse from the pre-amplifier. It has a maximum pulse height of about 300 mV. It was decided not to use a main amplifier as this pulse height is large enough for the threshold discriminator and the scaler. The operating voltage for the BF_3 tube was about 1220 V. For obtaining the pulse distribution with 400 channel analyser (Intertechnique) an amplifier had to be used (A 1002) at a gain setting of 10 and with a positive output pulse. The pulse height distribution shows two well-defined peaks. Resolution on the main peak (peak 2) which is produced by the $^{10}B(n,\alpha)^7Li$ reaction (transition to the first excited state 478 keV above ground state) was 11% and well within the limit of 15% for a good quality tube (1). The other peak (peak 1) occurs when the ^{7}Li nucleus is left in the ground state (about 5% of the cases). The pulse height distribution was also obtained by just using the threshold discriminator as shown in fig. 5. The operating voltage was adjusted at 1224 V to get the following relation between two different count rates $\dot{A}$ corresponding to the different discriminator settings :

$$\dot{A}(41\ \mathrm{mV}) = (17.5 \pm 0.5)\ \dot{A}(280\ \mathrm{mV}).$$

In obtaining the above relationship, the criterion given by De Pangher (1) is applied. The two counting rates are adjusted relative to each other. One chosen at a flat region in the pulse height distribution and the other in the region with maximum gradient. Thus $\dot{A}$(41 mV) in our case is the characteristics rate for the internal Am-Be source and is 26400 counts/min after dead time correction (dead time 4 μsec.). This characteristics rate is found to be reproducible within ± 0.3% for a counting time of only ten minutes. For all further measurements the threshold discriminator is permanently locked at 41 mV setting. Thus the calibration with the internal source was achieved and the PLC was set up and ready for further calibration under right conditions.

4. Calibration with external radio-active sources

For this purpose, a source positioning device (see fig. 2) was fabricated. With its help, the source can be positioned at a desired height above the ground and its distance from the PLC can be varied for inverse square measurements. The measurements were carried out in cabin 1 on flight path 15 of the linear accelerator (LINAC).

The room is about 5 x 4 x 3 cubic metres. The floor is of concrete. The inner walls are of thermocole with outer walls of bricks. The scatter contribution to be expected in the room is quite high. Also, it was not a very good place to do the calibration measurements because when the LINAC was operating and the flight path opening was closed with water, wax and lead to bring down the background to a low level. In these measurements, three well calibrated sources Am-Be, Ra-α-Be and Cf-252 were used to arrive at the effective centre and sensitivity values. Table IA gives the details of the source used. Inverse square measurements for all the three sources were done using at least twelve distances and giving sufficiently long runs to have good statistics. The PLC was at a height of 1 metre above the ground in all these measurements. The effect of the front part of the PLC carrier on the count rate was also measured and was found to be less than 0.5% for the same distance when the PLC was in the middle or in the extreme front. In all these measurements the PLC was fixed at the middle (fig. 2). These measurements are listed in tables II, III and IV. All the values are corrected for background and dead time loss. These data were analysed using the following equation given in (1)

$$\dot{A} = a + \frac{b}{(x+c)^2} \qquad (1)$$

TABLE IA.

Source	Emission Rate s^{-1}	Accuracy	Half life	Average Energy of neutrons
Am-Be*	2.35×10^6 s^{-1}	± 5 %**	458 Yrs.	4.5 MeV
Ra-α-Be*	6.52×10^6 s^{-1}	± 2 %***	1600 Yrs.	3.6 MeV
Cf-252(5)	1.50×10^6 s^{-1} (on 17th April 1970)	± 0.6%	2.65 Yrs.	1.5 MeV

* These sources are availble at CBNM.

** The Am-Be source was calibrated against the 10 Ci sources of KFA Jülich which for its part had been calibrated against the standard source of P.T.B. Braunschweig, West Germany.

*** The Ra-α-Be source was calibrated by $MnSO_4$ bath technique by Mr. van der Eijk of CBNM in April, 1964, having a source strength of 6.44×10^6 s^{-1} at that time. Correction for the growth of activity has been applied using the formula

$$S_{(t_o+t_1)} = S_{t_o} \frac{1 + 0.14(1-e^{-0.0357(t_o+t_1)}}{1 \times 0.14(1-e^{-0.0357\, t_o})}$$

The source was prepared in April, 1957, so $t_o = 7$ Yrs. (the diff. between this date and calibration date) $t_1 = 6$ yrs. the time elapsed since the last calibration.

$\dot{A}$ is the countrate (counts/min) at a distance, x, between the centre of the front face of the BF_3 tube and the centre of the source, 'a' is the contribution of the scattered neutrons and is dependent on scattering geometry. 'c' is the distance behind the centre of the front face of BF_3 tube where the effective centre lies and 'b' depends upon the source strength and is a measure of the sensitivity. These values of a, b, and c and their errors are obtained simultaneously using a least square fit computer programme, CERV, developed by Mr. Cervini of the Data Handling Section of the CBNM. Taking unit weights for each observation, it minimises the sum of the squares of the difference between the observed and calculated counting rates divided by the difference between the number of observations and the number of variables (three in our case). The values of a, b and c obtained in case of these sources are as given in table IB.

TABLE IB.

Source	a*	b	c
	min^{-1}	cm^2-min^{-1}	cm
Am-Be	159.5 ± 9.0	$(423.6 \pm 4.3) \times 10^5$	12.32 ± 0.38
Ra-α-Be	373.0 ±26.0	$(1159 \pm 9) \times 10^5$	11.61 ± 0.22
Cf-252	104.0 ± 7.0	$(273.9 \pm 1.9) \times 10^5$	9.93 ± 0.20

Sensitivity values for these sources were obtained using the equation

$$S = \frac{4\pi b}{\varepsilon Q} \qquad (2)$$

---

* Shadow shield measurements to determine the scatter contribution gave values about 40% higher. It may be due to the fact that the polyethylene cone itself changes the scattering conditions.

where ε is the anisotropy factor for the source used. Its value deviates from unity only for big sources. In our case the sources are small and so the value of ε has been taken to be one for all the above three sources. This flux-density sensitivity S depends on the energy and is independent of x. Its values are tabulated below in table IC.

TABLE IC.

Source	Sensitivity S (counts/min)/(neutron/cm^2-sec)	or counts/(neutron/cm^2)
Am-Be	227.0 ± 11.3	2.780 ± 0.188
Ra-α-Be	223.4 ± 4.5	3.723 ± 0.075
Cf-252	229.5 ± 2.0	3.825 ± 0.033

During all these measurements the characteristic rate was constant at 26400 counts/min. The ratio a/b which gives an idea as to scattering conditions in a particular geometry is given for the above three sources in table ID.

TABLE ID.

Source	a/b
Am-Be	$(3.8 \pm 0.2) \times 10^{-6}$
Ra-α-Be	$(3.2 \pm 0.3) \times 10^{-6}$
Cf-252	$(3.8 \pm 0.2) \times 10^{-6}$

The average value can be taken as 3.5×10^{-6}.
To see the effect of γ-rays on the copper BF_3 tube, the PLC was exposed continuously to Ra-α-Be source for three days delivering a dose of about 25 R.

But it was found that the count rate for this source was constant (to within ± 0.3%). The BF_3 tube resolution was unaffected and the characteristic rate was also constant as expected. Inverse square measurements were also carried out with a Sb-Be source and with three other photoneutron sources prepared here (6). The sources prepared here were La-D_2O, Na-D_2O and Na-Be with energies of neutrons as 0.16, 0.27 and 1.0 MeV respectively and were prepared by surrounding the respective γ-ray sources by a beryllium cylinder (8cm diameter, 8cm height with 2cm thickness of Be around the gamma source) or a glass cylinder containing heavy water (10cm diameter, 10cm height and 4cm thickness of D_2O around the gamma source). The purpose of these measurements was to determine the position of the effective centre for these energies. The data were obtained by doing measurements for short times (15 minutes) at each distance in view of very short half-lives of these sources and possibility of receiving lot of gamma dose. Therefore the errors for the values of a, b and c were rather high, but the mean values of 'c' obtained, 8.0, 8.4 and 8.6cm respectively, are quite satisfactory. Value of 'c' for Sb-Be source is found to be rather low, 5.8cm, and was found to be the same even when the measurements were repeated. In case of all these sources, the dimensions were quite large. In addition the high activities of γ-ray sources (10 Ci La, 5 Ci Na and 5 Ci Sb) might have affected the PLC. The exact effect of γ-rays on the count-rate must still be investigated with varying γ-ray doses.

The directional dependance measurements for Am-Be, Ra-α-Be, Cf-252 and Sb-Be sources were also carried out by rotating the PLC around its geometrical centre in steps of ten degrees. The measurements are presented in fig. 6 and an idea as to the effectiveness of the PLC shield can be obtained.

It can be said that with external radio-active sources, the measurements are relatively easier and good accuracy and reproducibility can be achieved.

5. Measurements with the monoenergetic neutrons

These measurements are divided into two parts ; (i) using $^{7}Li(p,n)^{7}Be$ and $T(p,n)^{3}He$ reactions to produce mono-energetic neutrons from 50 keV to 1.5 MeV with the Proton Recoil Proportional counter used as a comparison standard, (ii) using $D(d,n)^{3}He$ and $T(p,n)^{4}He$ reactions for higher energies with the Proton Recoil Telescope counter used as a comparison standard.

The selected experimental parameters for obtaining the various neutrons energies are shown in table V. This selection must take into account that there are two neutron counters to be compared which exludes the 0° direction for simultaneous measurements. Furthermore, one has to consider the angular distribution of the neutron producing reaction in that sense that the counters should not be positioned on a steep slope of this distribution. The counters should not approach each other to much near to 0° direction to avoid in scattering. The chosen angle relative to the incoming ion beam should not be associated with a too large neutron energy gradient which would worsen the energy resolution for small distances of the PLC too much.

The chosen parameters represent a compromise aiming at equal neutron energy spread contributions from the target and the detector at x = 2 m. If once the calibration could be achieved in this way one is not limited to some particular working conditions with accelerator neutrons. One can just select the bombarding particle energy and the angle at which the neutrons of the desired energy are emitted and do the flux density measurements with reasonable accuracy.

To carry out these measurements the PLC with its carrier was mounted on railings with wheels so that it could be positioned at the desired angle with respect to the target and can be moved on the railings to vary its distance from the target for inverse square measurements.

The Van de Graaff accelerator at CBNM can accelerate single charged positive ions up to the energies of 3.0 MeV. The target material forms a thin layer of 3 cm diameter evaporated on to metallic backings of 4 cm diameter. They are mounted in specially designed cans which are fitting to the accelerator beam extension. The target wobbles through a small angle and is cooled with a spray of air during beam bombardement.

5.1. Measurements with neutrons from 50 keV to 1.5 MeV

In this range six energies are selected. For 50 keV, 100 keV and 200 keV neutron energy the $^7Li(p,n)^7Be$ reaction is used and for 500 keV, 1.0 MeV and 1.5 MeV the $T(p,n)^3He$ reaction is used. The various bombarding particle energies, neutron observation angles to the incoming proton beam, the energy loss in each case, target thickness used and the operating conditions for the Van de Graaff accelerator are given in tables V and VI. Lithium targets are prepared in CBNM and are LiF layers on silver backings. Tritium targets have been obtained from NUKEM, West Germany and are TTi layers on copper backings.

In all these measurements, the Proton Recoil Proportional Counter (7, 8, 9, 10, 11) has been used as a monitor for the neutron fluence. The Proportional counter used was CP 1 from Dr. Paulsen of CBNM (10) which is based on the design of A.T.G. Ferguson (9), shown in fig. 7 with some slight modifications. It consists of a cylindrical aluminium cathode of 5 cm inner diameter (0.025 cm wall thickness for keeping neutron scattering as low as possible), a central anode wire of 0.01 cm diameter of molybdenum and a soft steel housing of 0.04 cm wall thickness. The sensitive volume is defined by field tubes as described by Cockroft and Curran (11). These field tubes are at ground potential whereas the anode wire and cathode are at positive and negative potentials respectively with potential ratios ($\frac{V_+}{V_+ + V_-}$) according to (11). The spectrum is obtained on a 256channel analyser and a typical spectrum is shown in fig. 8. Fluence determinations by means of the proportional counter are accurate to about ± 3%.

Operating conditions of the proportional counter for various energies are given in table VII and the method of evaluation and actual evaluation are given in table VIII. A beam current integrator is used as a sort of preliminary neutron fluence monitor by relating the results to a certain beam charge at each distance for inverse square measurements. The proportional counter is also positioned at the same angle as the PLC on the other side of the incoming beam and at a distance of 80 cm between the target and its front face (which actually corresponds to a distance of 96.23 cm for fluence evaluation). The proportional counter spectrum is recorded for each PLC position for monitoring purpose, but evaluation of neutron fluence is done only for the PLC at x = 1.5 m. A background measurement with shadow shield between target and proportional counter is also done. The two spectra, foreground and background, are obtained on paper tape, from which they are transferred on to data cards for the computer program FTPRA for the evaluation of the total number C of recorded recoils (see table VIII) by making a fit with the theoretical spectrum at the energy used. For the remaining measurements the flat portion in the proportional counter spectra is used as an index of the fluence variation to correct the PLC counts. In case of all these energies (except 500 keV), this method of evaluation was used and the value of characteristic rate was 27231 c/min being higher than the original value of 26400 c/min. When transfer of PLC from LINAC to Van de Graaff was done, the cable used between the pre-amplifier and the threshold discriminator now is extremely long. A terminator with 50 Ω resistance was put at the threshold discriminator side and the characteristic rate restored to the original value. Measurements at 500 keV were done with and without this terminator and the ratio between the number of counts was found to be same as the ratio between the two characteristic rates. Further measurements were done with the characteristic rate at 26400 c/min and the b values obtained with the remaining energies have been corrected for by this factor.

In case of 500 keV the old long counter available here which is based on the Hanson-McKibben design but with polyethylene parts instaed of paraffin was used as the relative monitor. It was kept at a distance of about three metres from the target making an angle of ninety degrees to the direct beam. It could act as a good monitor. A study of the characteristics of the beam current integrator also revealed that it could be used as a relative monitor because it is supposed to have a precision of ± 1%. The inverse square data for all the six energies are listed in tables IX, X, XI, XII, XIII, XIV and values of a, b, and c obtained by the method used in case of external radioactive sources are given in table XV. It can be seen from this table that the value of the scattered contribution in each case is different, obviously due to different scattering geometry used every time; and its value depends also on the reaction used. But in general the value of a is quite small and ratio a/b $< (4.0 \times 10^{-6})$. The mean value of 'c' obtained in each case is now fixed because in actual fluence evaluation one would take a fixed value of 'c' for the particular energy used (one could also fix 'a',as in reference (15), but as shall be seen in the suggested procedure later on, we eliminate 'a' and thus scattering geometry is of no importance), and the values of 'a' and 'b' are obtained again with their errors. This value of 'b' with its error is used for the sensitivity evaluation. The sensitivity in this case is now defined by

$$S = \frac{b}{\Phi\ 1.0\ \text{cm}} \quad \text{counts/(neutron/cm}^2\text{)} \qquad (3)$$

where Φ 1.0 cm is the neutron fluence at one cm due to the same number of charges as in the case of the least squares fit run for each point. Relation (3) is obtained from the equation (2) in the following way

$$S = \frac{4\,\pi\,b}{Q}$$

and

$$\phi = \frac{Q}{4\,\pi\,r^2} \quad \text{neutrons/cm}^2\text{-sec at } r\,\text{cm} \qquad (4)$$

and at one cm

$$\phi\ 1.0\ \text{cm} = \frac{Q}{4\,\pi} \quad \text{neutron/cm}^2\text{-sec}$$

$$S = \frac{b}{\phi 1.0\ \text{cm}} \quad \text{(counts/min)/(neutron/cm}^2\text{-sec} \qquad (5)$$

in case of radioactive neutrons sources where one can count rate $\dot{A}$. In case of the measurements with monoenergetic neutrons where we take total number of counts A, we have

$$S = \frac{b}{\Phi\ 1.0\ \text{cm}} \quad \text{counts/(neutrons/cm}^2\text{)}$$

The sensitivity values for all the energies duly corrected for the characteristic rate variation are given in table XVI, and mean values of 'c' are also tabulated.

5.2. Energies of 2.5 MeV and above

In this case, the neutrons were produced by using $D(d,n)^{3}He$ and $T(d,n)^{4}He$ reactions. Only three energies 2.5, 6.0 and 15.0 MeV were selected. The various operating conditions are given in tables V and VI. The inverse square data obtained with these energies are given in tables XVII, XVIII and XIX. Throughout these measurements, the beam current integrator only was used as a monitor at each distance by giving same beam charge at each distance. The values of a, b and c obtained are given in the following table :

E_n	a	b	c
2.5 MeV	$(2277\pm 216)\mathrm{x}10^{2}$	$(375\pm 81)\mathrm{x}10^{7}$	11.10 ± 0.85
6.0 MeV	$(3041\pm 145)\mathrm{x}10^{2}$	$(2534\pm 59)\mathrm{x}10^{7}$	14.45 ± 0.80
15.0 MeV	$(752\pm 186)\mathrm{x}10^{2}$	$(4686\pm 85)\mathrm{x}10^{7}$	18.30 ± 0.65

For sensitivity evaluation, the recoil telescope counter based on the design of S.J. Bame et al. (12, 13) and shown in fig. 9 was used. In the telescope counter, recoil protons from a thin hydrogeneous radiator foil proceed through two pill-box type proportional counters and a solid angle defining exit aperture at forward angles relative to the incoming neutrons.

Only a small fraction of the proton energy is lost in the proportional counters. The recoil protons are then detected in a surface barrier or a scintillation counter. The differential pulse height distribution of these counters when gated with the triple coincidences of all the three counters exhibits a line spectrum for incident monoenergetic neutrons (see fig. 10). The telescope counter is supposed to have an accuracy of ± 2 to 3% for neutron fluence evaluation.

The operating conditions of the telescope for the three energies are given in table XX and the method of evaluation in table XXI. The sensitivity values obtained in the first instance were as follows :

E_n	$S = \frac{b}{\Phi\ 1.0\ \text{cm}}$	η (E)
2.5 MeV	4.310	1.11
6.0 MeV	4.990	1.29
15.0 MeV	2.663	0.69

In case of 2.5 MeV and 6.0 MeV the sensitivity values are found to be rather high. An effort was made to investigate the reasons for this. There could be three reasons, (i) one that the PLC was counting the neutrons of all the energies while the telescope counter was counting the neutrons only of the particular energy,(ii) the measurements with the telescope counter were not performed correctly or (iii) in this region of 2 MeV and above the carbon scattering resonances also become important and this definitely can also be one of the reasons in the increase of sensitivity.

To investigate the first point, measurements were done with a dummy target which is nothing but the copper backing used in case of the actual targets. The measurements were done at a distance of 150 cm and the number of counts corresponding to both the energies were 265,214 (for 100 charges) and 466,180 (for 50 charges). Now these counts are designated a' and the following relation is used to re-evaluate the value of b

$$\dot{A} - a' = \frac{b}{(x+c)^2}$$

where x = 150 cm and c = 11.1 and 14.45 for the respective energies, this gives the values of b as follows :

E_n	$b_{corrected}$
2.5 MeV	3115×10^7
6.0 MeV	2077×10^7

and then the sensitivity values are reduced to

E_n	counts/(neutron/cm^2)	η (E)
2.5 MeV	4.23	1.09
6.0 MeV	4.07	1.05

These values are still a bit too high, it is felt. To investigate the second point the measurements with the telescope counter were repeated in case of 6.0 MeV and 15.0 MeV and surprisingly enough quite a difference was noted in the new and previous measurements. These measurements must still be repeated. The results obtained in this case are not rather satisfactory though an attempt has been made to arrive at a solution. In case od 15.0 MeV, the sensitivity drops down which is quite normel (1).

The procedure to be followed while working with D(d,n) neutrons should be modified as follows. At each distance for inverse square measurements, exposure must be given using the actual target and then using the dummy target. The values obtained in case of dummy target must be subtracted from the actual values at each distance. This, it is hoped, will lead to satisfactory results.

6. Use of the PLC for neutron fluence or calibration of a neutron source

The following procedure is proposed for finding the Q value of a neutron source or arriving at the neutron fluence at a particular point.

(1) Using the internal source, find out the characteristic rate. It should be (26400 ± 80) counts/min after dead time correction. If it is lower, the subsequent measurements must be increased by the ratio of the two characteristic rates and vice versa.

(2) The neutron source and the PLC must be properly positioned with respect to each other. Now, two measurements should be done, for sufficiently long time, at two distance $x_1 = 90$ cm and $x_2 = 110$ cm and the values of the count rate put in the following equation.

$$\dot{A} = a + \frac{b}{(x+c)^2} \qquad (1)$$

and also the value of 'c' for the particular energy used (see table XXII) should be obtained. Then the following equation can be applied :

$$S = \frac{4\pi b}{Q} \quad \text{(counts/min) / (neutron/cm}^2\text{-sec)}$$

for the case of a neutron source whose Q value is to be determined and where counts/min are taken in the equation (1)

or $$S = b/\phi_{1.0\ \mathrm{cm}} \ \text{counts/(neutron/cm}^2\text{)},$$

where total number of counts are taken and put in the equation (1) in case where neutron flux is to be evaluated.

The substituting the values from the figure XII and the mean value of S as 232.8 (counts/min) / (neutron/cm^2-sec) or 3.88 counts/(neutron/cm^2) we can obtain the S value for the particular energy used by

$$S = 232.8 \times \eta\,(E) \ \text{(counts/min) / (neutron/cm}^2\text{-sec)}$$

or $$S = 3.88 \times \eta\,(E) \ \text{counts/(neutron/cm}^2\text{)}$$

and then

$$Q = \text{Emission Rate} = \frac{4\pi b}{232.8 \times \eta(E)} \quad \text{n/sec}$$

or $$= \text{Fluence at 1.0 cm} = \frac{b}{3.88\,\eta(E)} \quad \text{n/cm}^2$$ can

be arrived at.

One can use this method of evaluation in any type of scattering geometry and no other relations need be defined if the scattering rate can be assumed constant in the region where the PLC is moved. This procedure can be followed in case of radioactive neutron sources and accelerator produced neutrons. For neutrons produced from D(d,n) reaction, the procedure may have to be modified. For each distance a run with dummy target should be carried out and then, if $\dot{a}'_1$ and $\dot{a}'_2$ are the count rates obtained at the two distances respectively, and if $\dot{A}_1$ and $\dot{A}_2$ are the counts with the actual target, we have

$$\dot{A}_1 - \dot{a}_1 = \frac{b}{(x_1 + c)^2}$$

$$\dot{A}_2 - \dot{a}'_2 = \frac{b}{(x_2 + c)^2}$$

and further evaluation can be done as before.

7. Discussion of results

Table XXII gives the following values - the position of the effective centre, sensitivity and efficiency (normalized to the energy 1.0 MeV) for all the energies used. Fig. 11 gives a plot of the 'c' values with energy and fig.12 gives the efficiency curve. An attempt has been made to arrive at the energy calibration of the PLC. With radioactive neutron sources, it could be achieved rather easily. 'c' values obtained correspond to those of De Pangher (1). The accuracy, of course, is limited by the accuracy of the source used. In case of accelerator produced neutrons, the results with neutrons produced from the reactions using proton beams are quite satisfactory. The values of 'c' obtained in this case are a bit higher as compared to those obtained in case of radioactive sources. The possible explanation can be that in this case we have monoenergetic neutrons while in the case of radioactive neutron sources an average energy is taken because there are neutrons of energies up to 11 MeV. The measurements with D(d,n) reaction neutrons are rather complicated. The inverse square data measurements have yielded quite good results, but the sensitivity evaluation is not satisfactory. A solution for working with these neutrons is proposed and the measurements must still be continued. In case of 15.0 MeV neutrons, the trend must be confirmed by taking at least one more energy around this point. In addition, the sensitivity of the PLC must also be investigated.

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TABLE II

Inverse Square Data - Radio-active Sources

1. Source Am-Be

Distance x cms.	Net Counts / min $\dot{A}$
70	6412
80	5124
90	4220
100	3509
110	2986
120	2577
130	2249
140	1995
150	1770
160	1591
170	1427
180	1305
190	1196
200	1096

Characteristic Rate = 26,400 c/min

TABLE III

Inverse Square Data - Radio-active Sources

2. Source Ra-α-Be

Distance x cms.	Net counts / min $\dot{A}$
50	30876
60	23010
70	17778
80	14232
90	11614
100	9625
110	8164
120	7015
130	6132
140	5420
150	4808
160	4349
165	4088
170	3910
180	3558
190	3227
200	2953

Characteristic Rate = 26,400 c/min

TABLE IV

Inverse Square Data - Radio-active Sources

3. Source Cf - 252

Distance x cms.	Net counts / min $\dot{A}$
50	7734
60	5696
70	4393
80	3495
100	2372
110	2000
120	1734
130	1506
140	1332
150	1170
165	996
190	786

Characteristic Rate = 26,400 c/min

TABLE V

Monoenergetic Neutron Energies Used from the Van de Graaff Accelerator

Neutron Energy	Reaction	Proton or Deuteron Energy	Angle	Target Thickness	Energy Spread keV / mg - cm^{-2}			Compare with
					due to target	due to detector	Total	
50 keV	$Li^7(p,n)^7Be$	2050 keV	126°	80 $\mu g/cm^2$	± 2.5	± 6	± 6.5	The Proportional Counter
100 keV		2150 keV	128°	159 $\mu g/cm^2$	± 5.3	± 12	± 13	
200 keV		2250 keV	106°	390 $\mu g/cm^2$	± 12.5	± 25	± 28	
500 keV	$T(p,n)^3He$	2830 keV	125°	0.934 mg/cm^2	± 28	± 60	± 66	
1.0 MeV		1920 keV	26°	1.089 mg/cm^2	± 52	± 78	± 94	
1.5 MeV		2370 keV	20°	1.089 mg/cm^2	± 47	± 80	± 93	
2.5 MeV	$D(d,n)^3He$	1500 keV	104°	2.8 mg/cm^2	± 37	± 217	± 220	The Telescope Counter
6.0 MeV		3000 keV	20°	1.3 mg/cm^2	± 61	± 210	± 217	
15.0 MeV	$T(d,n)^4He$	1000 keV	75°	2.8 mg/cm^2	± 251	± 380	± 455	

TABLE VI

Operating Conditions for the VdG Accelerator :

E_n	E_p or E_d	Target	Thickness	E'_p or E'_d keV	Frequency MHz
50 keV	2050 keV	LiF	80 $\mu g/cm^2$	2050	19.357
100 keV	2150 keV	LiF	160 $\mu g/cm^2$	2160	19.870
200 keV	2250 keV	LiF	390 $\mu g/cm^2$	2275	20.390
500 keV	2830 keV	TTi	0.934 mg/cm^2	2873	22.916
1.0 MeV	1920 keV	TTi	1.089 mg/cm^2	1970	18.974
1.5 MeV	2370 keV	TTi	1.089 mg/cm^2	2418	21.023
2.5 MeV	1500 keV	DTi	2.8 mg/cm^2	1785	25.554
6.0 MeV	3000 keV	DTi	1.3 mg/cm^2	3082	33.555
15.0 MeV	1000 keV	TTi	2.8 mg/cm^2	1361	22.290

TABLE VII

The Proportional Counter (CP1)

Operating Conditions :

E_n	Gas and Pressure	Temp.
50 keV	580 torr. H_2 + 20 torr. CH_4	26.2° C
100 keV	580 torr. H_2 + 20 torr. CH_4	26.2° C
200 keV	580 torr. H_2 + 20 torr. CH_4	26.2° C
500 keV	760 torr. CH_4	23° C
1.0 MeV	760 torr. CH_4	23° C
1.5 MeV	1250 torr. CH_4	23° C

Ratio $\frac{V+}{V_+ + V_-} = 0.702$

Multi-channel Analyser Used : 0002404 TMC
256 channels

Gain Coarse 8 Fine 1
Baseline 0.3 V Input Polarity Negative

High tension used depends upon the gas filling and to be adjusted till the spectrum is completely spread over all the 256 channels.

TABLE VIII

The Proportional Counter

Neutron fluence Evaluation :

a) Method of evaluation

$$\phi = \frac{C \cdot f_1 \cdot f_2}{N \cdot \sigma} \quad \text{n/cm}^2 \text{ at counter position (96.23 cm)}$$

C = total number of recorded proton recoils, extrapolated to zero pulse height (determined from PROGRAM FTPRA)

f_1 = dead time correction

f_2 = scattering correction

N = number of hydrogen atoms in the sensitive counter volume

σ = n-p scattering cross-section for the energy used.

(b) Actual Evaluation

Energy	$C \cdot f_1 \cdot f_2$	N	σ barns	$\Phi_{96.23\ \text{cm.}}$	$\Phi_{1.0\ \text{cm.}}$
50 keV	126,399	1.393×10^{22}	15.557	583,290	540.1×10^{7}
100 keV	106,459	1.393×10^{22}	12.790	597,410	553.2×10^{7}
200 keV	67,295	1.393×10^{22}	9.7005	497,998	461.1×10^{7}
500 keV	119,103	3.453×10^{22}	6.161	279,926	259.2×10^{7}
1.0 MeV	214,250	3.453×10^{22}	4.259	1,458,115	1350.2×10^{7}
1.5 MeV	270,495	5.679×10^{22}	3.414	1,397,704	1294.3×10^{7}

TABLE IX

Inverse Square Data - Monoenergetic Neutrons

1. Neutron Energy : 50 keV

Distance x cms.	No. of Counts/900 charges A
60	4,681,965
70	3,552,829
80	2,773,422
90	2,296,093
110	1,630,322
120	1,402,336
130	1,213,583
140	1,069,864
150	938,626
170	739,798
190	617,856
200	561,047

Characteristic Rate = 27, 231 c/min

TABLE X

Inverse Square Data - Monoenergetic Neutrons

2. Neutron Energy : 100 keV

Distance x cms.	No. of Counts/340 charges A
60	4,825,670
70	3,640,368
80	2,920,772
90	2,373,463
110	1,649,701
120	1,420,172
130	1,220,690
140	1,057,492
150	950,605
160	847,687
180	698,559
190	633,918
200	574,545

Characteristic Rate = 27,231 c/min

TABLE XI

Inverse Square Data - Monoenergetic Neutrons

3. Neutron Energy : 200 keV

Distance x cms.	No. of Counts/100 charges A
60	3,906,754
70	3,000,706
80	2,371,216
110	1,309,245
120	1,140,198
130	972,643
140	848,549
150	759,800
160	674,981
170	616,252
180	557,054
190	507,234
200	464,027

Characteristic Rate = 27,231 c/min

TABLEXII

Inverse Square Data - Monoenergetic Neutrons

4. Neutron Energy : 500 keV/ 30 charges

Distance x cms.	No. of Counts A
60	2,197,645
70	1,694,300
80	1,346,786
90	1,087,703
100	901,016
110	747,052
120	645,244
130	560,422
140	497,038
150	440,873
160	396,305
170	355,627
180	322,691
190	294,240
200	270,303

Characteristic Rate = 26,400 c/min

TABLE XIII

Inverse Square Data - Monoenergetic Neutrons

5. Neutron Energy 1.0 MeV

Distance x cms.	No. of Counts/100 charges A
60	10,990,150
70	8,436,066
90	5,434,133
100	4,472,563
110	3,771,994
120	3,208,404
130	2,769,253
140	2,409,496
150	2,107,496
170	1,697,098
190	1,424,818
200	1,261,240

Characteristic Rate = 27,231 c/min

TABLE XIV

Inverse Square Data - Monoenergetic Neutrons

6. Neutron Energy 1.5 MeV

Distance x cms.	No. of Counts/60 charges A
70	7,780,862
80	6,213,280
90	5,040,702
100	4,155,880
110	3,507,176
120	2,988,749
140	2,274,615
150	1,989,329
170	1,604,532
190	1,309,405
200	1,182,611

Characteristic Rate = 27,231 c/min

TABLE XV

Values of the constants a, b and c :

E_n	a	b	c	Characteristic rate c / min.
50 keV	(904 ± 252) x 10^2	(2108 ± 90) x 10^7	7.90 ± 1.35	27231
100 keV	(686 ± 162) x 10^2	(2209 ± 60) x 10^7	8.25 ± 0.90	27231
200 keV	(448 ± 127) x 10^2	(1785 ± 49) x 10^7	7.90 ± 0.90	27231
500 keV	(317 ± 62) x 10^2	(1030 ± 23) x 10^7	8.90 ± 0.75	26400
1.0 MeV	(266 ± 174) x 10^2	(5406 ± 64) x 10^7	10.2 ± 0.40	27231
1.5 MeV	(439 ± 228) x 10^2	(5067 ± 101) x 10^7	10.85 ± 0.75	27231

TABLE XVI

Sensitivity values :

E_n	c cms.	b	$b_{corrected}$ for ch.Rate	$\varnothing_{1.0\text{ cm.}}$ *	$S = \frac{b}{\varnothing_{1.0\text{cm.}}}$	Efficiency $\eta(E)$
50 keV	8.0	$(2115 \pm 11) \times 10^7$	$(2050 \pm 11) \times 10^7$	540×10^7	3.796	0.980
100 keV	8.0	$(2193 \pm 7) \times 10^7$	$(2126 \pm 7) \times 10^7$	553×10^7	3.840	0.990
200 keV	8.0	$(1791 \pm 5) \times 10^7$	$(1736 \pm 5) \times 10^7$	461×10^7	3.790	0.980
500 keV	8.9	$(1031 \pm 3) \times 10^7$	$(1031 \pm 3) \times 10^7$	259×10^7	3.98	1.026
1.0 MeV	10.2	$(5401 \pm 11) \times 10^7$	$(5236 \pm 11) \times 10^7$	1350×10^7	3.88	1.00
1.5 MeV	10.8	$(5062 \pm 11) \times 10^7$	$(4907 \pm 11) \times 10^7$	1294×10^7	3.79	0.980

* Proportional Counter has an accuracy of ± 3 %.

TABLE XVII

Inverse Square Data - Monoenergetic Neutrons

7. Energy 2.5 MeV

Distance x cms.	No. of counts/100 charges A
60	6,519,102
70	5,061,001
80	4,042,132
90	3,331,475
100	2,780,971
110	2,379,499
120	2,096,302
130	1,859,796
140	1,640,317
150	1,465,631
160	1,313,278
170	1,182,787
180	1,085,525
190	990,167

Characteristic Rate = 26,400 c/min.

TABLE XVIII

Inverse Square Data - Monoenergetic Neutrons

8. Energy 6.0. MeV.

Distance x cms.	No. of counts/50 charges A
60	4,897,655
70	3,861,850
80	3,145,056
90	2,627,742
100	2,244,400
110	1,944,322
120	1,725,000
130	1,531,000
140	1,384,348
150	1,234,222
160	1,146,288
170	1,067,286
180	962,195
190	893,246

Characteristic Rate = 26,400 c/min.

TABLE XIX

Inverse Square Data - Monoenergetic Neutrons

9. Energy 15.0 MeV

Distance x cms.	No. of counts/80 charges A
60	7,714,562
70	6,084,114
80	4,923,595
90	4,099,876
100	3,426,172
110	2,895,793
120	2,544,894
130	2,173,741
140	1,935,233
150	1,737,225
160	1,542,158
170	1,399,590
180	1,278,761
190	1,158,400
200	1,063,010

Cahracteristic Rate = 26,400 c/min.

TABLE XX

The Recoil Telescope Counter

Operating Conditions :

1 Counters used : Two Proportional Counters (counters 1&2) and surface barrier detector at 2.5 MeV or Cs I scintillation counter at 6.0 MeV and 15.0 MeV (Counter 3).

2 Distance between the target and E-detector = (250 + 6)
= 256 mm

3

Proportional Counters :	Gas filling	E_n
operating voltage 1000 V	Argon + 5%CO_2 at 63torr.	2.5 MeV
for 2.5 & 6.0 MeV	Argon + 5%CO_2 at 150torr.	6.0 MeV
neutrons and		
1100 V for 15.0 MeV	Krypton+5%CO_2 at 183torr.	15.0 MeV
neutrons		

Cs I scintillation Counter : HT on PM tube 1300 V

4 Gain of the amplifiers :

Counters	1	2	3	Threshold	E_n
	29	33	35	2V each	- 2.5 MeV
	29	33	190	2V each	- 6.0 MeV
	39.5	39.5	100	2V for 1, 2 3V for 3	- 15.0 MeV

5 TMC used 0002404 : Input Polarity +
Connections from delay unit out Amp. Input
gate Coinc Input

Gain	Coarse	32	Fine 1

6 Telescope Foil :

E_n	Foil No.
2.5 MeV	2
6.0 MeV	3
15.0 MeV	4
For background	5

TABLE XXI

The Recoil Telescope Counter.

Neutron fluence evaluation :

(a) Method of evaluation

$$\phi = \frac{C\ \mathrm{corr.}}{\epsilon}\ \mathrm{n/cm^2}\ \text{at 1 cm.}$$

where $C_{\mathrm{corr.}}$ = (No. of counts in the foreground run)-
-No. of counts in the background run)

$\times f_1 \times f_2$

f_1 = Dead time correction

$$= \frac{1}{1 - 5 \times 10^{-6} \times \sum_i Ni}$$

Ni = No. of counts/sec. in each of the three counters of the telescope

f_2 = 1.025 (Absorption at entrance in Al.)
x 1.010 (Absorption in the wires of the Prop. Counters)

= 1.03525

ϵ = M (4 MeV, 256 mm) . f . P . σ

where M (4 MeV, 256mm) = 1.781×10^{-4}

$$f = \text{Corr. factor} = \frac{M(E_n, 256mm)}{M(4, 256mm)}$$

P = No. of hydrogen atoms in the polyethylene foil used

σ = n-p scattering cross-section for the H_2 for the energy used

Recoil Telescope Counter

(b) Fluence Evaluation

E_n	C_{corr}			ϵ				$\varnothing_{1.0cm} = \frac{C_{corr}}{\epsilon}$	$\varnothing_{1.0cm}$ corrected
	C	f_1	f_2	M(4,256)	f	P	σ_{np}	n/cm^2	for no. of charges
2.5MeV	5285	1.0052	1.03525	1.781x 10^{-4}	0.999	1.1 x 10^{20}	2.547x 10^{-24}	1104 x 10^8 for 1500 charges	73.6 x 10^8
6.0MeV	8870	1.0030	1.03525	1.781x 10^{-4}	1.003	5.1 x 10^{20}	1.421x 10^{-24}	713 x 10^8 for 700 charges	51 x 10^8
15.0MeV	18670	1.0045	1.03525	1.781x 10^{-4}	1.03	2.97x 10^{21}	0.6484 x 10^{-24}	550 x 10^8 for 250 charges	176 x 10^8

TABLE XXII

E_n or $\bar{E}$	Source	c cm.	S counts/n-cm^{-2}	η (E)
50 keV	$Li^7(p,n)^7Be$	8.0	3.796	0.980
100 keV	$Li^7(p,n)^7Be$	8.0	3.840	0.990
200 keV	$Li^7(p,n)^7Be$	8.0	3.790	0.980
500 keV	T $(p,n)^3He$	8.9	3.980	1.026
1.0 MeV*	T $(p,n)^3He$	10.2	3.880	1.000
1.5 MeV	T $(p,n)^3He$	10.8	3.790	0.980
1.5 MeV	Cf - 252	10.0	3.825	0.986
2.5 MeV	D $(d,n)^3He$	11.1	4.230	1.090
3.6 MeV	Ra-α-Be	11.6	3.723	0.960
4.5 MeV	Am-Be	12.4	3.78	0.974
6.0 MeV	D $(d,n)^3He$	14.5	4.070	1.050
15.0 MeV	T $(d,n)^4He$	18.3	2.663	0.690

* Value of η(E) taken as 1.0 at this energy.

Figure Captions

Fig. 1 : Cross sectional view of the PLC

Fig. 2 : Measuring device

Fig. 3 : Plateau of the BF_3 tube

Fig. 4 : Output pulse from the pre-amplifier

Fig. 5 : Pulse height distribution

Fig. 6 : Directional response of the PLC

Fig. 7 : Cross sectional view of the proton recoil proportional counter

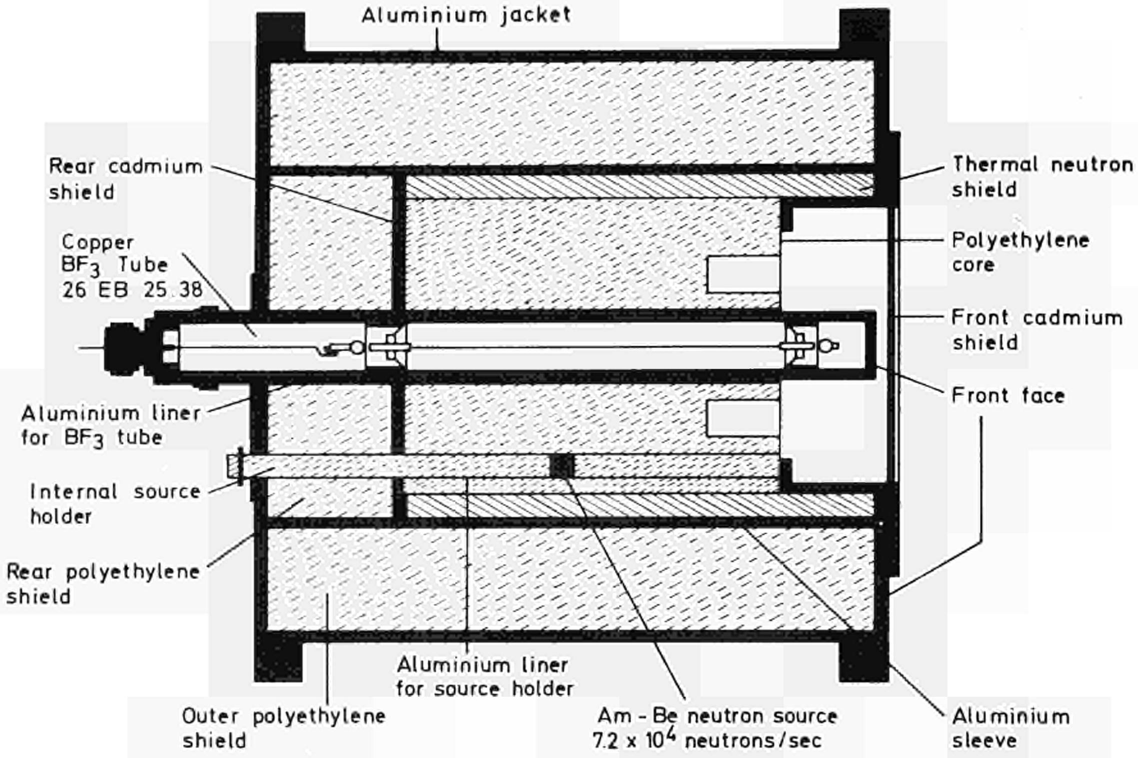
Fig. 8 : Typical spectrum obtained with the proton recoil proportional counter

Fig. 9 : Cross sectional view of the recoil telescope counter

Fig. 10 : Typical spectrum obtained with the proton recoil telescope counter

Fig. 11 : c - values as a function of the neutron energy

Fig. 12 : Efficiency curve of the PLC



Schematic diagram of precision long counter showing BF$_3$ tube and internal neutron source.

Fig. 1

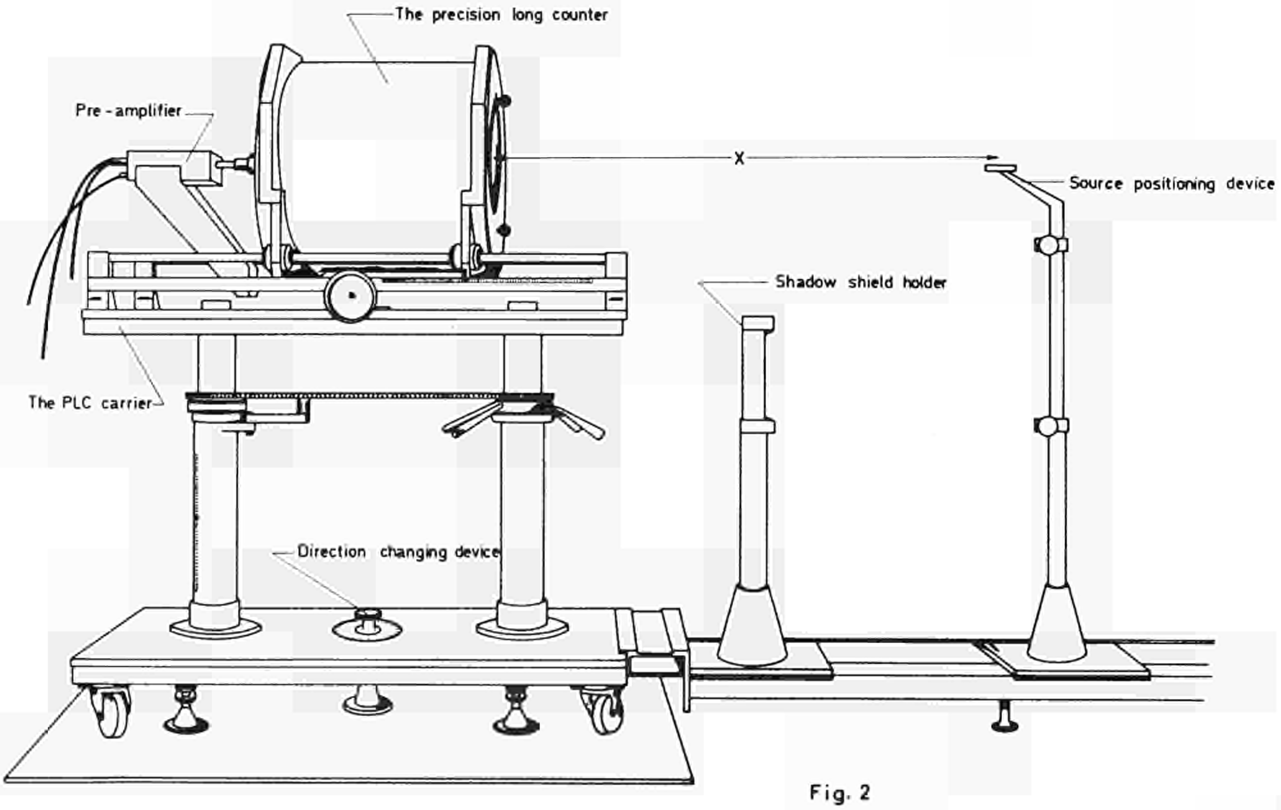
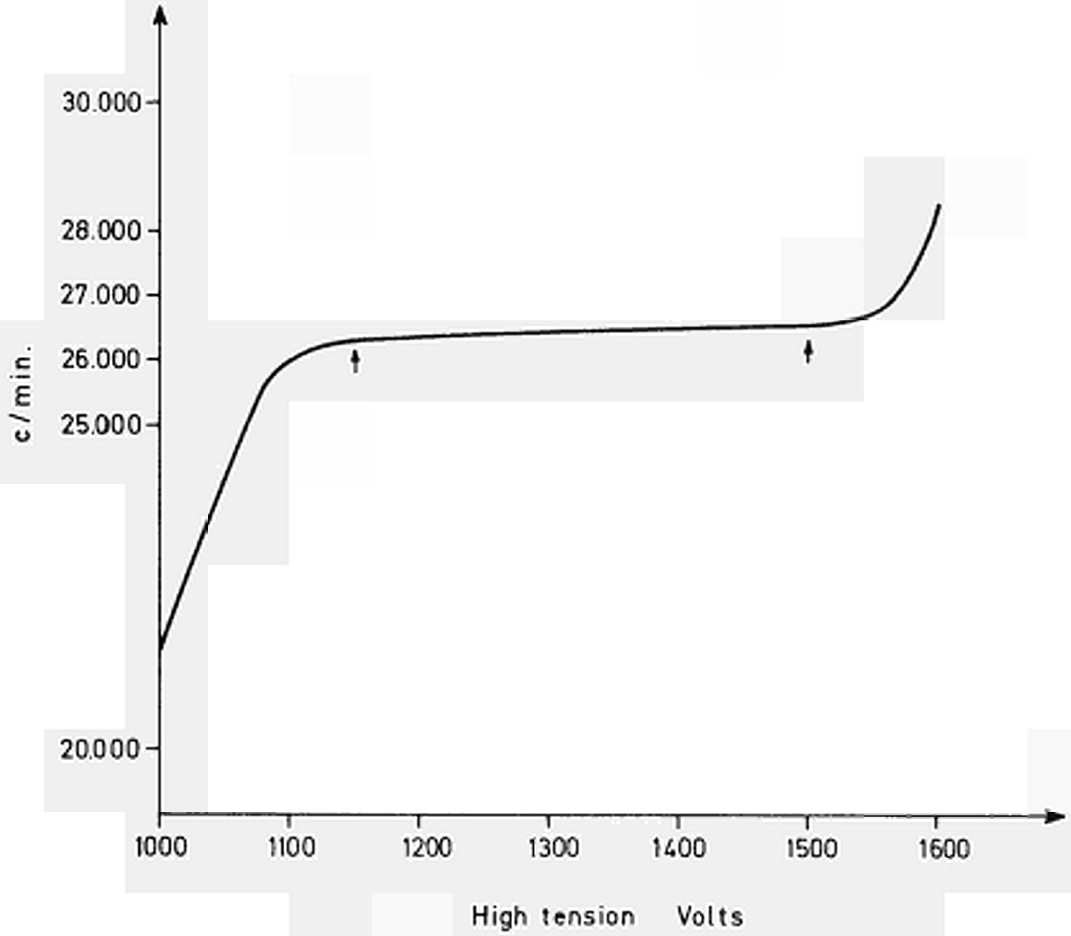
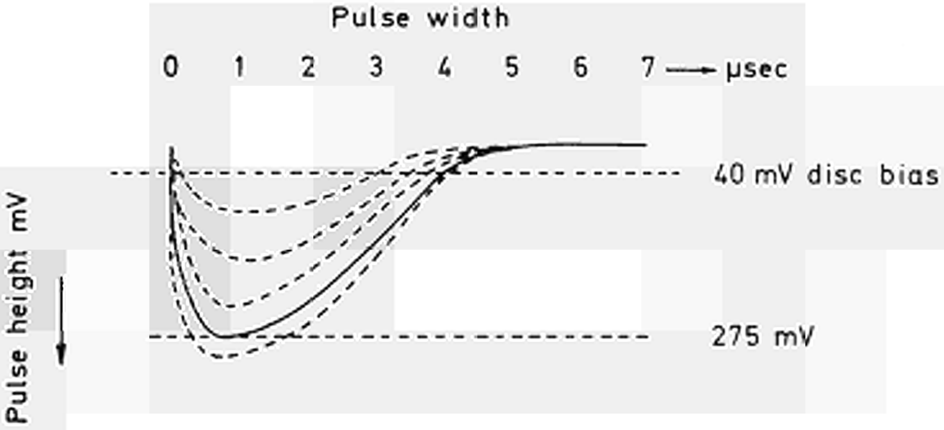


Fig. 2



Plateau for the BF_3 tube (26 EB 25.38)
Disc. bias = 40 mV

Fig. 3



Output pulse from the pre - amplifier

Fig. 4

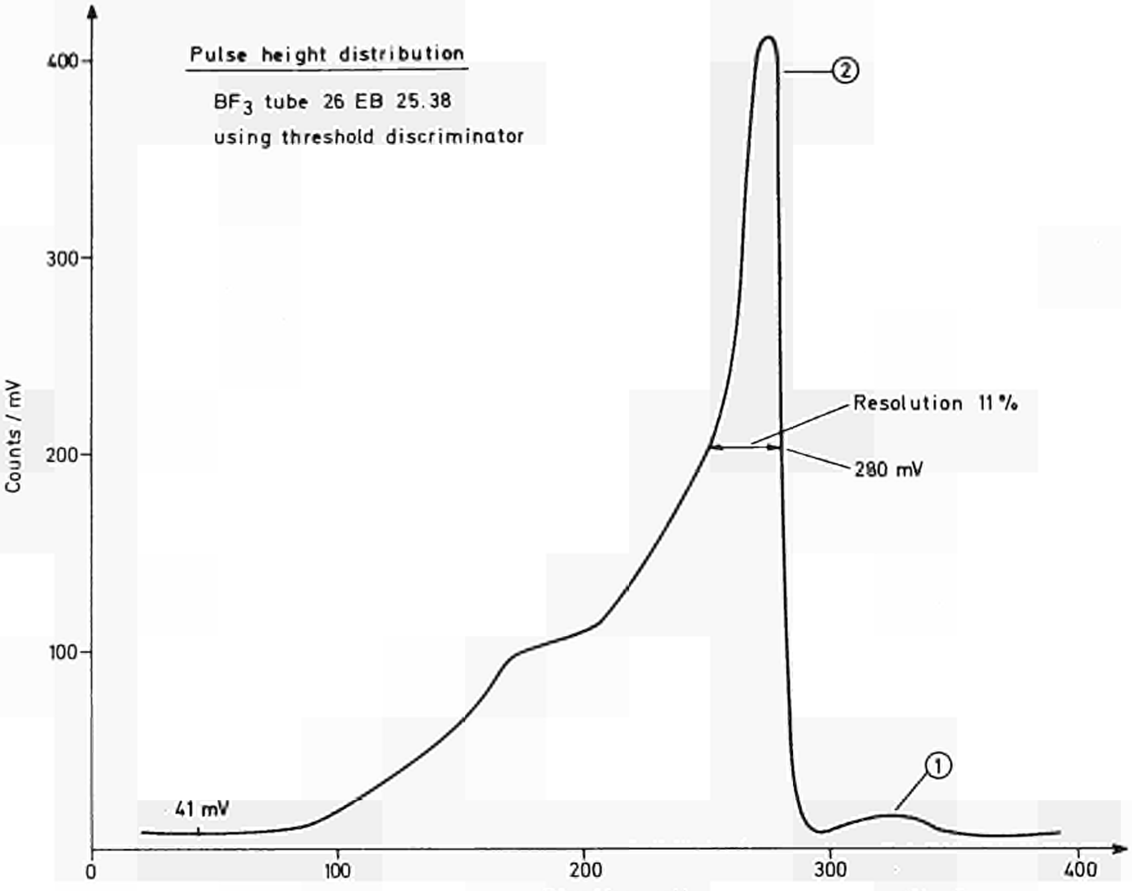

Pulse height distribution
BF$_3$ tube 26 EB 25.38
using threshold discriminator
②
Resolution 11 %
280 mV
①
41 mV
Counts / mV
400
300
200
100
0
100
200
300
400
Disc bias mV

Fig. 5

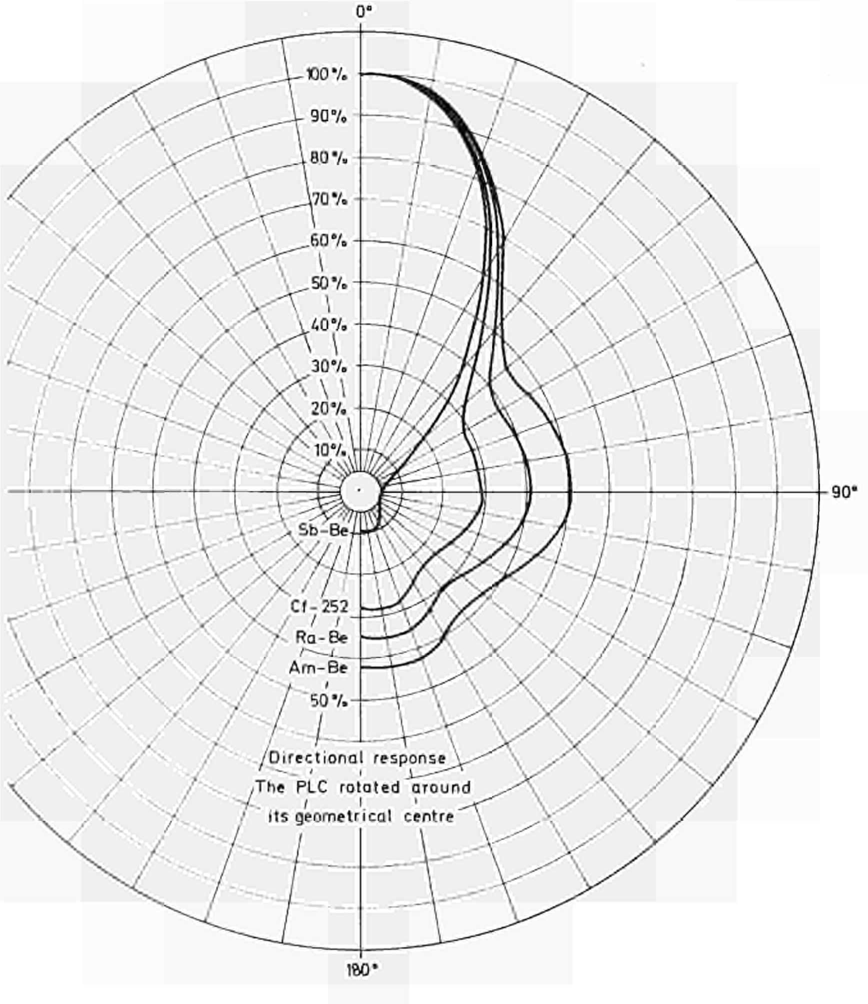
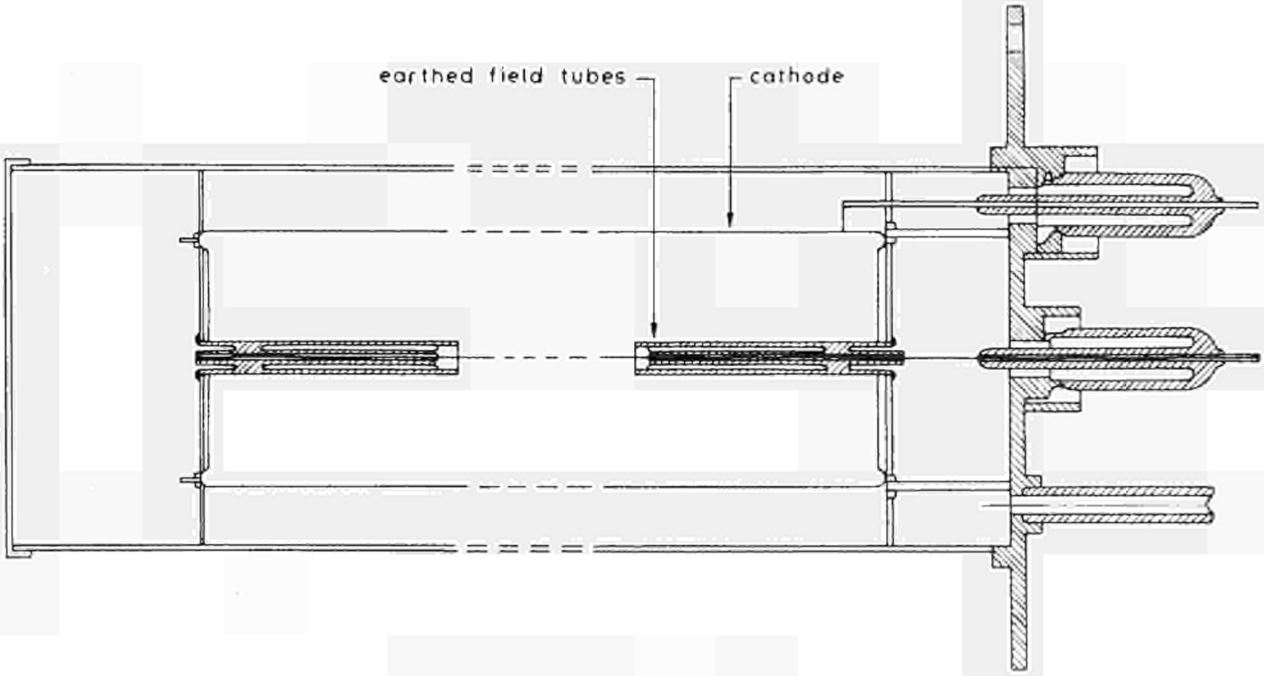
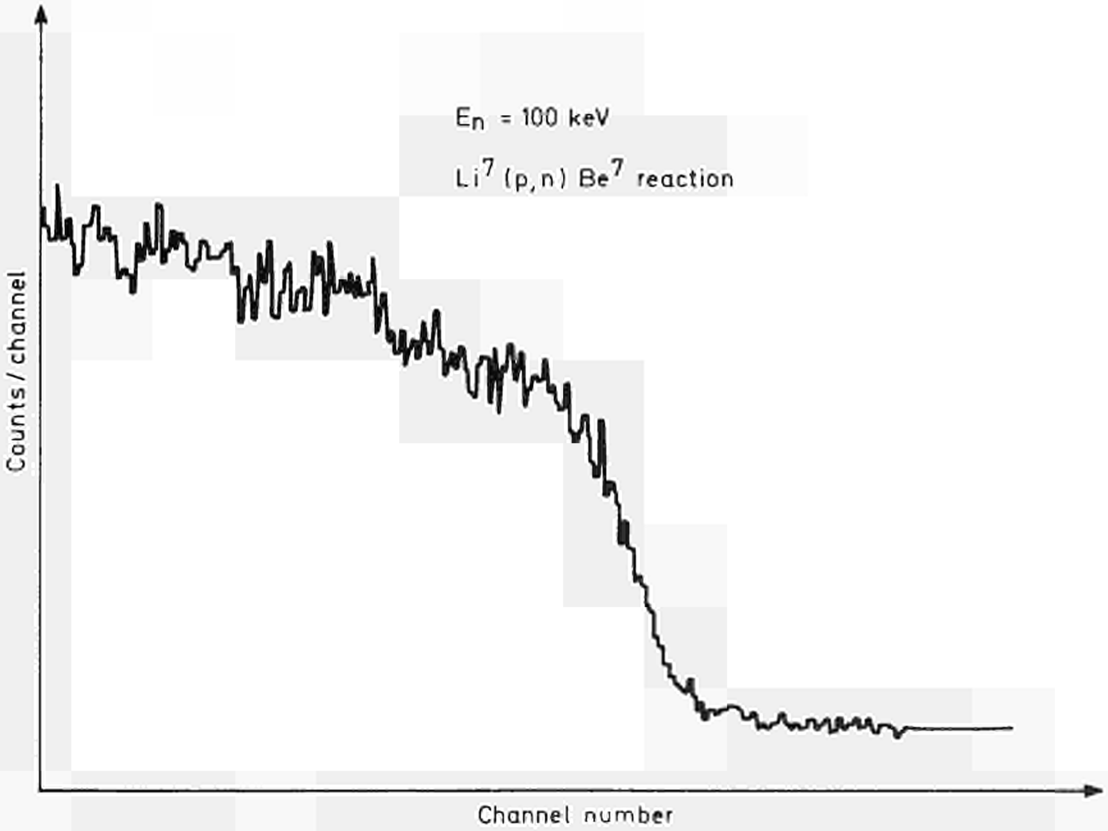

0°
100 %
90 %
80 %
70 %
60 %
50 %
40 %
30 %
20 %
10 %
Sb-Be
Cf-252
Ra-Be
Am-Be
50 %
90°
180°
Directional response
The PLC rotated around
its geometrical centre

Fig. 6



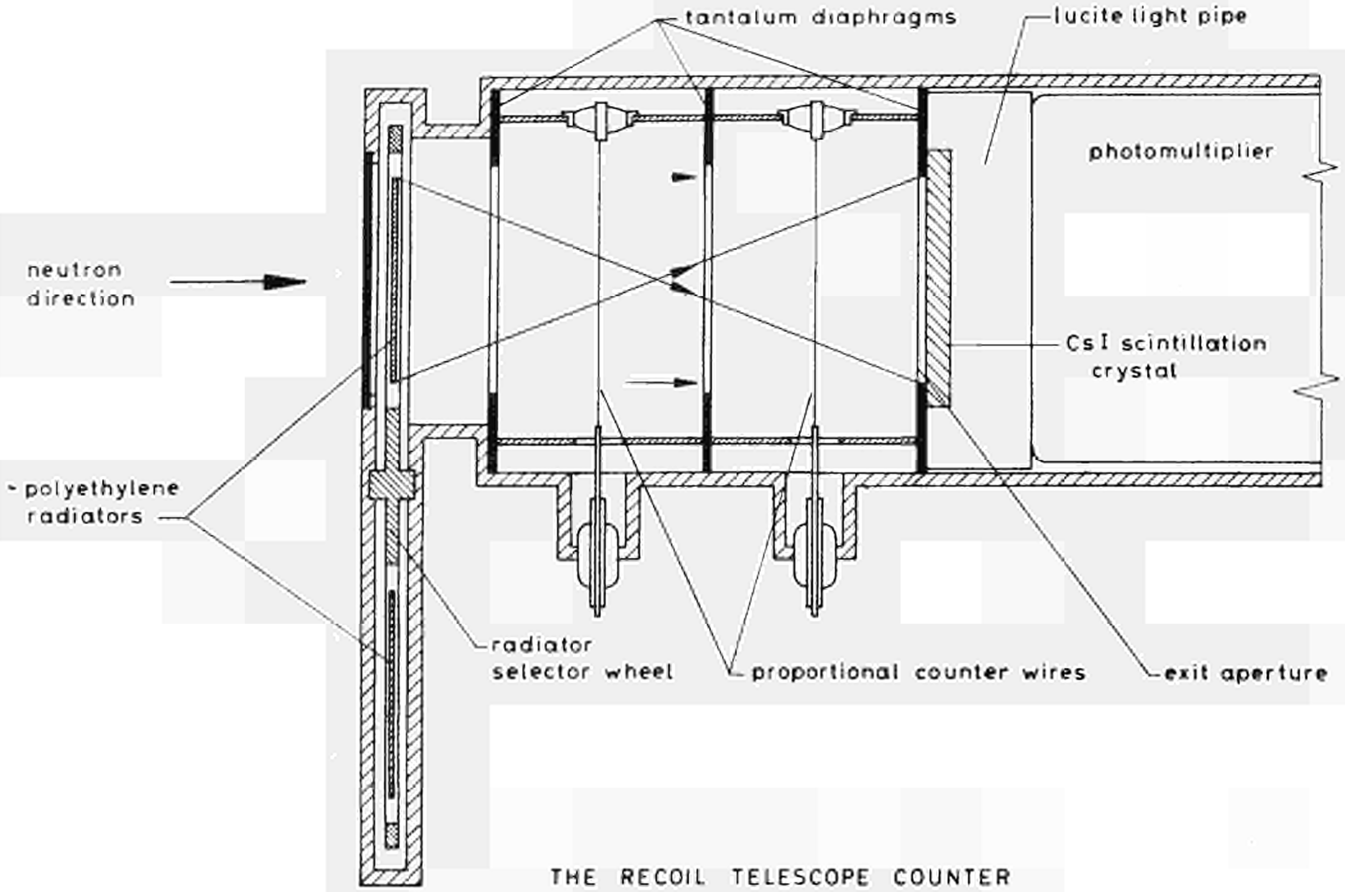
THE PROPORTIONAL COUNTER

Fig 7



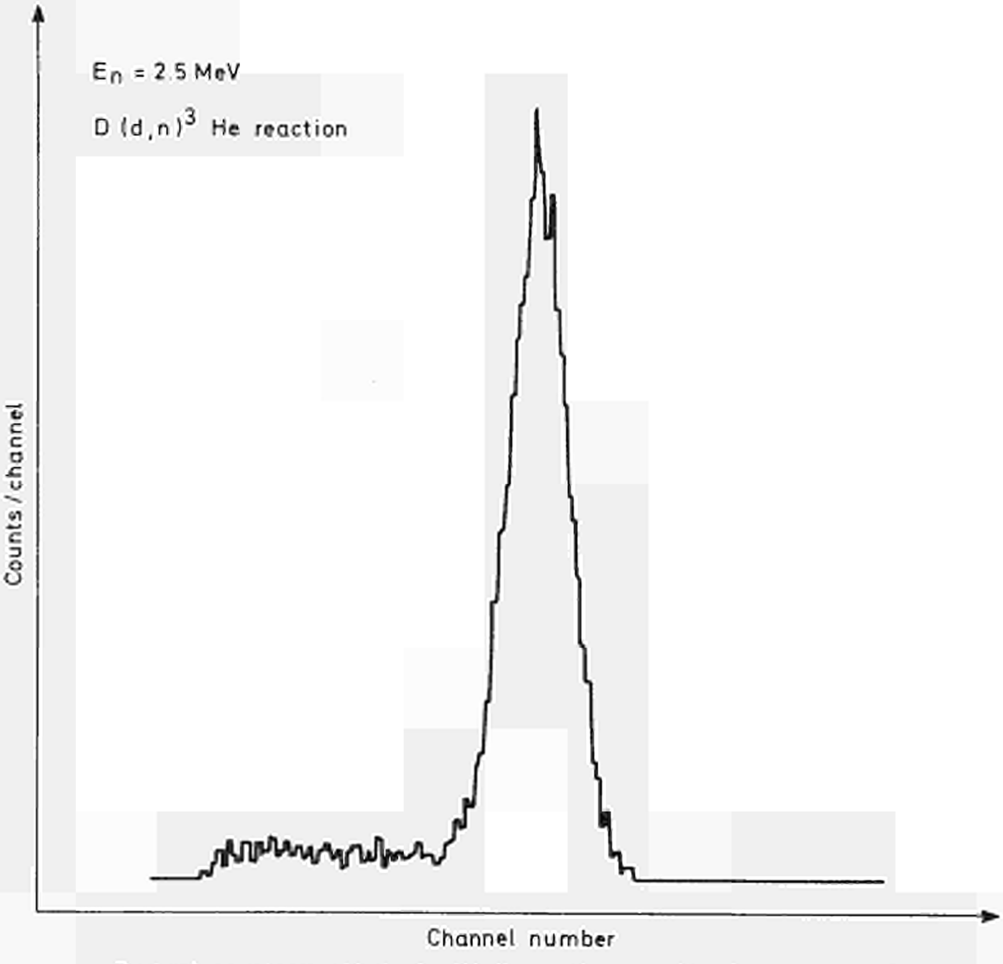
Typical spectrum obtained with the proton recoil proportional counter (CP1)

Fig. 8



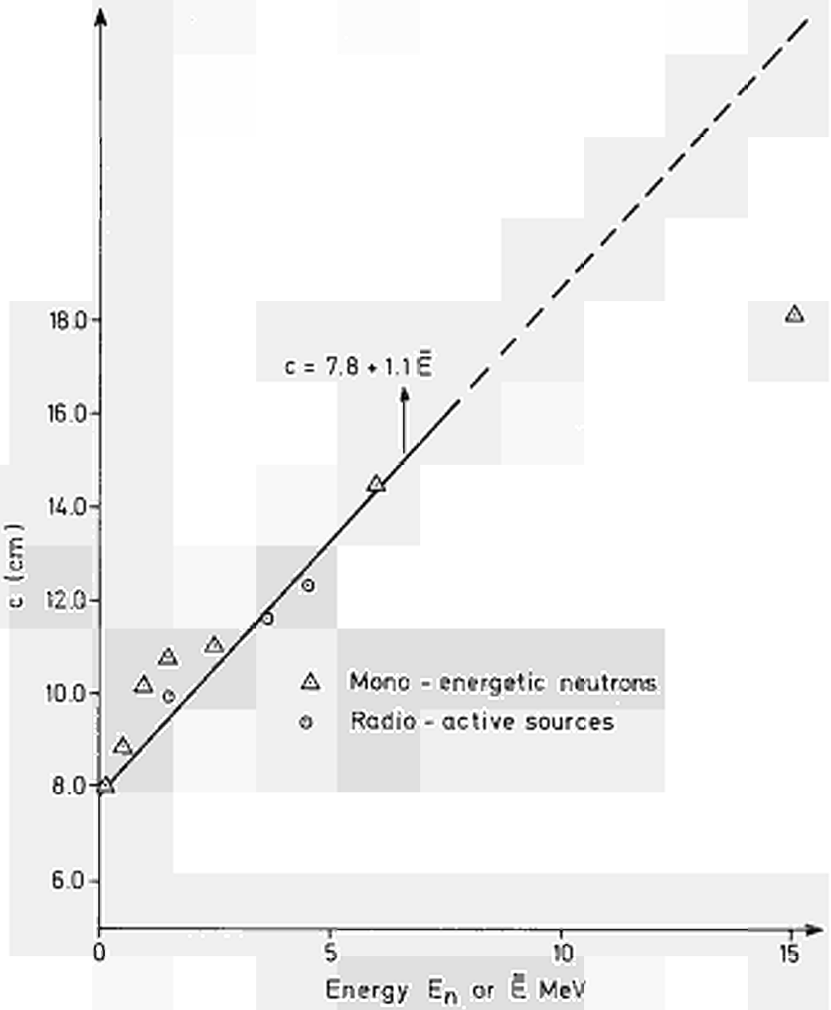
THE RECOIL TELESCOPE COUNTER

Fig.9



Typical spectrum obtained with the proton recoil telescope counter

Fig. 10



c -values of the PLC

Fig. 11

Efficiency curve for the PLC

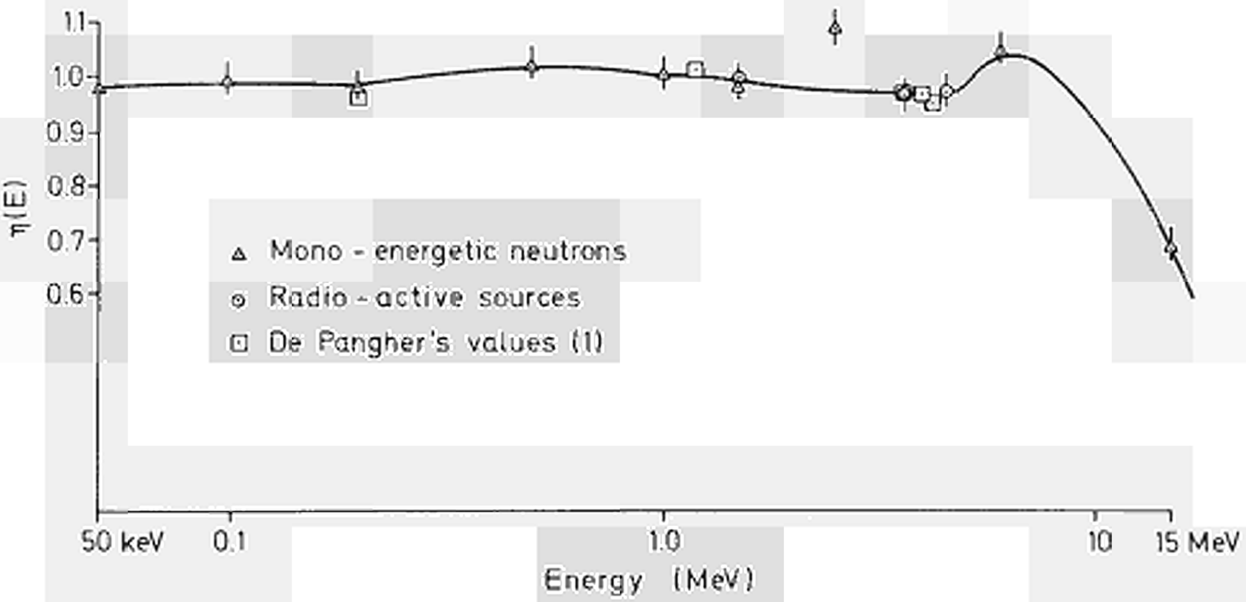


Fig. 12

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>
> Alfred Nobel

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